Elaboration of a sustainability assessment method for neighbourhoods

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Preface

5 years ago… I had just finished my internship at evr-Architecten, an architecture office specialized in sustainable construction. Concerned about environmental issues, I was looking for a new challenge. Following an idea formulated a few years before by my master thesis supervisor, professor Frank De Troyer, I decided to apply for a doctoral research.

5 years later…time flies! I am writing the last lines of this PhD dissertation looking back at the fantastic years gone by, both from a professional and human perspective. I would like to thank all those who contributed directly and indirectly to this doctoral research.

First of all, I would like to express my deepest gratitude to my supervisors, professor Frank De Troyer and professor Karen Allacker, for giving me the opportunity to carry out this research. Frank, thank you for your support and confidence during the past years. Your door was always open to discuss methodological issues and answer all my questions. Karen, thank you for your regular feedback and enthusiasm but also for the opportunity to further pursue my research work at the KU Leuven in the coming months.

Furthermore, I would like to thank all the jury members for the time spent reading my (rather extensive) manuscript but also for their constructive feedback. Special thanks to professor Alexander Passer for offering me the possibility to work as a guest professor at the TU Graz next semester. Wim, I am looking forward to be one of your colleagues next year at VITO.

In the course of this PhD dissertation, I was involved in various research projects financed by the Public Waste Agency of Flanders (OVAM). Thank you to all the colleagues from VITO, BBRI and the VUB for sharing their knowledge and for the fruitful collaboration!

Many thanks to all former and current colleagues of the division of Architectural Engineering for the interesting discussions and pleasant coffee and lunch breaks. Thank you Lien, Bernard, Tam and Ayu for your collaboration on research and publications! A special mention goes to the colleagues of the Green Office for the great atmosphere and positive distraction, especially in the last work-intensive months of this research.

Je ne voudrais pas oublier de remercier mes parents pour leur soutien inconditionnel dans tous mes projets. Même si elle pouvait parfois me lasser, je pense que la phrase: "Comment va ton doctorat ?" va finir par me manquer… Un grand merci également maman, papa, Benoît, Céline, Eline et Michaël pour votre aide dans l’organisation de la réception!

Om af te sluiten, verdienen nog een aantal mensen een bijzondere vermelding in het d(r)ankwoord. Roxane, Lien, Jef, Jeroen, Evelien, Wouter, Willem en Delphine, bedankt voor de leuke gesprekken rond een pintje (of meer), de AoE en gezelschapsspellenavonden, de memorabele reis in Finland en nog meer!

Damien Trigaux
Leuven, December 2017

Contents

Summary

In the past decade, the neighbourhood scale has gained importance in the field of sustainable construction. To support designers and building stakeholders in the design of sustainable buildings and neighbourhoods, several sustainability assessment tools have been developed. Among these tools, a distinction can be made between scoring tools and Life Cycle Assessment (LCA) tools. Scoring tools assign scores to a number of criteria covering a wide range of sustainability issues, such as energy use, material use, water use, user transport and comfort. LCA tools are based on a systematic study of the environmental impacts caused during the entire life span of the building or neighbourhood. Although LCA tools are preferred because of their transparency and scientific base, current tools are mostly limited to the assessment of individual buildings and only cover the environmental dimension of sustainability.

In this PhD research a sustainability assessment method for neighbourhoods is developed using an integrated life cycle approach. This integrated approach combines an assessment of the economic, environmental and social performance of neighbourhoods, together with an assessment of the neighbourhood qualities. The assessment method is based on an existing assessment method for buildings, SuFiQuaD (i.e. Sustainability, Financial and Quality evaluation of Dwelling types), which is extended to the neighbourhood scale level and refined to include additional evaluation aspects related to operational energy use, operational water use, neighbourhood land use, user transport and neighbourhood qualities.

To deal with the complexity of the neighbourhood, a hierarchic assessment structure in line with the principles of the "element method for cost control" and a subdivision in various scale levels, is implemented. The approach, which is translated in a modular spreadsheet tool, is applicable during the various design stages, from rough estimations in the master planning to detailed impact calculations in later design stages.

The assessment method is applied to analyse the impact of neighbourhood elements (i.e. neighbourhood infrastructure and open spaces) and to compare four neighbourhood models with various layouts and built densities. First, the analysis reveals that neighbourhood elements have a non-negligible contribution to the neighbourhood impact, especially in low built density neighbourhoods, where these contribute to about 20% and 30% of the environmental and financial impact of material use respectively. Second, the comparison between neighbourhoods built according to former building practice (before the 1970s energy crisis) and current building practice (year 2017) shows the high influence of the construction standards. The environmental and financial impact of the neighbourhoods in line with the current practice is about 60% and 30% lower respectively, which is mainly a consequence of the stricter energy performance requirements. Third, the comparison between the neighbourhood models reveals the high influence of the urban form and built density. When considering the current building practice, environmental and financial impact reductions up to 10% and 20% respectively are obtained for the neighbourhood model with the highest built density, compared to the model with the lowest built density. Appropriate urban planning and

denser neighbourhood layouts are therefore recommended to reduce the impact of the built environment.

Finally, the assessment method is compared with a number of well-known scoring tools for neighbourhoods. The analysis of various sustainability measures reveals many discrepancies between the life cycle impact results and the scores awarded in scoring tools, confirming that the use of scoring tools is not a guarantee for a reduction of the environmental and financial impact of neighbourhoods. Based on this analysis, recommendations are formulated to better capture environmental and financial issues in scoring tools.

Samenvatting

Het voorbije decennium is de schaal van de wijk een belangrijke focus geworden bij duurzaam bouwen. Om ontwerpers en actoren in de bouwsector te ondersteunen bij het ontwerpen van duurzame gebouwen en wijken, werden verschillende duurzaamheidsevaluatietools ontwikkeld. Binnen die veelheid aan tools kan het onderscheid gemaakt worden tussen scoresystemen en levenscyclusanalyse (LCA) tools. Scoresystemen kennen scores toe aan verschillende criteria die een groot aantal duurzaamheidsaspecten evalueren, zoals energieverbruik, materiaalgebruik, waterverbruik, gebruikerstransport en comfort. LCA tools zijn gebaseerd op een systematische studie van de milieu-impact over de gehele levenscyclus van het gebouw of de wijk. Hoewel LCA tools de voorkeur krijgen omwille van hun transparantie en wetenschappelijke basis, zijn huidige tools meestal beperkt tot de schaal van het individuele gebouw en houden ze slechts rekening met de ecologische dimensie van duurzaamheid.

In dit doctoraatsonderzoek wordt een duurzaamheidsevaluatiemethode voor wijken ontwikkeld, gebruik makend van een geïntegreerde levenscyclusaanpak. Deze geïntegreerde aanpak combineert een evaluatie van de economische, ecologische en sociale prestaties van wijken, samen met een evaluatie van de wijkkwaliteiten. De evaluatiemethode is gebaseerd op een bestaande evaluatiemethode voor gebouwen, SuFiQuaD (Sustainability, Financial and Quality evaluation of Dwelling types), die naar de schaal van de wijk wordt uitgebreid. Bovendien wordt de methode verfijnd door de integratie van volgende aspecten: energieverbruik en watergebruik in de gebruiksfase, wijklandgebruik, gebruikerstransport en wijkkwaliteiten.

Om met de complexiteit van de wijkschaal om te gaan, wordt een hiërarchische structuur uitgewerkt. Deze evaluatiestructuur is gebaseerd op de principes van de “elementenmethode voor kostenbeheersing” en bestaat uit een onderverdeling in verschillende schaalniveaus. Deze aanpak wordt vertaald naar een modulaire rekentool en is bruikbaar tijdens de verschillende ontwerpfasen, vertrekkend van ruwe schattingen tijdens de masterplan fase tot gedetailleerde berekeningen in de latere ontwerpfasen.

De evaluatiemethode wordt toegepast om de impact van wijkelementen (wijkinfrastructuur en open ruimten) te analyseren en om vier wijkmodellen met verschillende layouts en bouwdichtheden met elkaar te vergelijken. Uit deze analyse blijkt ten eerste dat wijkelementen een niet-verwaarloosbare bijdrage leveren tot de wijkimpact, in het bijzonder in wijken met een lage bouwdichtheid waar ze respectievelijk tot ongeveer 20% en 30% van de milieu- en financiële impact van het materiaalgebruik bijdragen. Ten tweede toont de vergelijking tussen wijken gebouwd volgens de vroegere bouwpraktijk (voor de 1970 energiecrisis) en de huidige bouwpraktijk (jaar 2017) de hoge invloed van de bouwstandaarden. De milieu- en financiële impact van wijken in lijn met de huidige praktijk is respectievelijk ongeveer 60% en 30% lager, wat vooral het gevolg is van strengere energieprestatie-eisen. Ten derde toont de vergelijking tussen de wijkmodellen de hoge invloed van de stedenbouwkundige vorm en bouwdichtheid. Voor de huidige bouwpraktijk

worden reducties in milieu- en financiële impact tot respectievelijk 10% en 20% verkregen voor het wijkmodel met de hoogste bouwdichtheid, vergeleken met het model met de laagste bouwdichtheid. Een weloverwogen stadsontwikkeling en compactere wijklayouts worden daarom aangeraden om de impact van de gebouwde omgeving te reduceren.

Ten slotte wordt de evaluatiemethode vergeleken met een aantal bekende scoresystemen voor wijken. De analyse van verscheidene duurzaamheidsmaatregelen toont veel verschillen tussen de levenscyclusimpact-resultaten en de scores toegekend in scoresystemen. Hierdoor wordt er bevestigd dat het gebruik van scoresystemen geen garantie biedt voor een reductie van de financiële en milieu-impact van wijken. Op basis van deze analyse worden aanbevelingen geformuleerd om milieu- en financiële beschouwingen beter te integreren in scoresystemen.

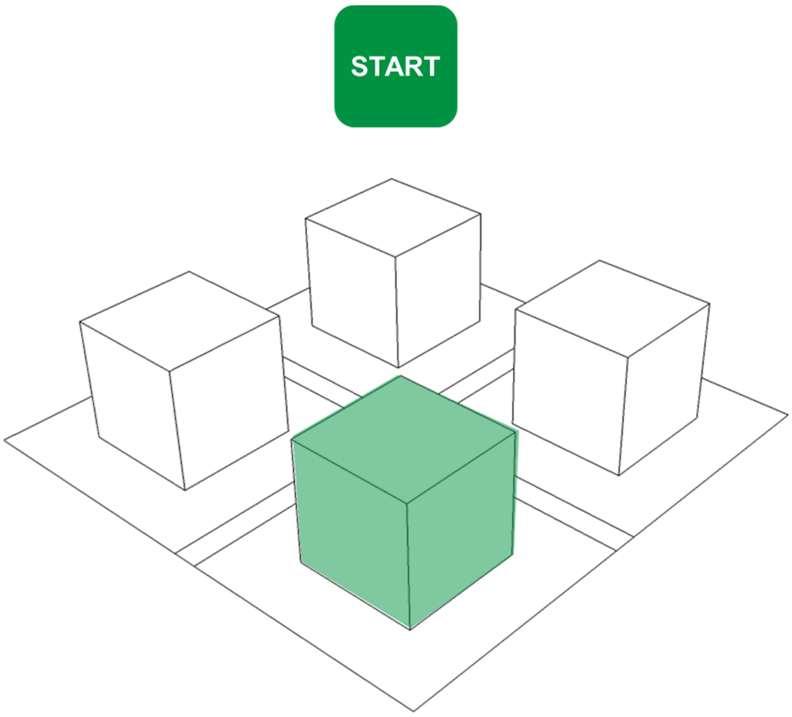
List of acronyms

ANB	Agentschap voor Natuur en Bos (Agency for Nature and Forests)
AP	Acidification Potential
BB/SfB	Belgische Bouw – Bâtiment Belge / Samarbetskommitten för Buggnadsfragor
BBRI	Belgian Building Research Institute
BIM	Building Information Modelling
BREEAM	Building Research Establishment Environmental Assessment Method
BSA	Building Sustainability Assessment
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
CEN	European Committee for Standardisation
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen (German Green Building Council)
DPWB	Diensten voor de Programmatie van het Wetenschapsbeleid (Services for the Programming of Science Policy)
DZM wijken	Duurzaamheidsmeter wijken (Sustainability assessment tool for neighbourhoods)
EHDD	Equivalent Heating Degree Days
E-LCA	Environmental Life Cycle Assessment
EP	Eutrophication Potential
EPC	Energy Performance Certificate
EOL	End-Of-Life
EPB	Energy Performance of Buildings
GWP	Global Warming Potential
IEA	International Energy Agency
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
MCA	Multi-Criteria Analysis
MMG	Milieugerelateerde Materiaalprestatie van Gebouwelementen (Environmental performance of building elements)
OVG	Onderzoek Verplaatsingsgedrag (Research on Transport Behaviour)
ODP	Ozone Depletion Potential
PHPP	Passiv Haus Projectierungs Paket (Passive house project package)
PDF	Potentially Disappeared Fraction of species
POCP	Photochemical Ozone Creation Potential

SIA	Swiss Society of Engineers and Architects
S-LCA	Social Life Cycle Assessment
SuFiQuaD	Sustainability, Financial and Quality Evaluation of Dwelling Types
TFA	Total Floor Area
TML	Transport & Mobility Leuven
UFA	Useful Floor Area
VAT	Value Added Tax
VITO	Vlaams Instituut voor Technologisch Onderzoek (Flemish Institute for Technological Research)
VEA	Vlaams Energieagentschap (Flemish Energy Agency)
VMM	Vlaamse Milieumaatschappij (Flanders Environment Agency)
VMSW	Vlaamse Maatschappij voor Sociaal Wonen (Flemish Company for Social Housing)

CHAPTER 1

Introduction



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1.1 Background

1.1.1 Sustainable development

With the increasing concern for environmental issues, sustainable development is to date a hot issue in research and policy development. In the report “Our common future” of the United Nations, sustainable development is defined as “a development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987).

Despite the general character of this definition, there is a broad consensus that sustainable development should incorporate three components, namely the economic, environmental and social pillars (UN General Assembly 2005). As these pillars are interdependent, a balance between them should be found when striving for sustainability.

However, consumer choices and decisions are to date mainly based on economic considerations. As the market price of products does not (fully) reflect their environmental and social impact, these aspects are often neglected when comparing different alternatives. To tackle this issue, the external costs caused by environmental (and social)[1] impacts, can be estimated and added on top of the financial cost in order to stimulate sustainable decisions. This concept was already applied in previous research focussing on the building sector (Allacker 2010; Allacker et al. 2013) and will be used in this PhD research.

1.1.2 Sustainable construction

The building sector has a major impact on the environment. In Europe, this sector is responsible for about 50% of the use of natural resources, 40% of the energy consumption and 16% of the water use (Ebert et al. 2011). Buildings are furthermore responsible for 36% of the total CO_2 emissions in the EU (European Commission 2017).

To reduce the impact of buildings, past and current policies have especially focussed on the impact of operational energy use. In the European EPBD Directive (European Union 2003; European Union 2010), the energy certification of buildings and the application of minimum requirements on the building energy performance have been introduced.

However, the current policies are evolving to a more holistic approach of sustainable construction. In the European standards on the sustainability of construction works (CEN 2010; CEN 2011; CEN 2014; CEN 2015), the sustainability of buildings is defined as a combination of the economic, environmental and social performance, taking into account the technical and functional requirements.

Besides the building level, the higher scale of the built environment has become an important focus in sustainable decision taking. Urban sprawl, which characterises the Belgian building

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[1] The concept of external cost can be applied to social impacts but is not included in this research.

stock, has a major impact on required infrastructure, energy use, land use and local mobility (European Environment Agency 2006). In order to move towards a sustainable built environment, neighbourhoods need to be planned and organized differently, focussing not only on the characteristics of individual buildings but also on the urban layout, built density and relations between buildings and their surroundings. The neighbourhood scale and the methods to assess the neighbourhood sustainability are the subject of this PhD dissertation.

1.1.3 Building sustainability assessment tools

To support designers and building stakeholders, several Building Sustainability Assessment (BSA) tools have been developed. Among these tools, a distinction can be made between scoring tools and Life Cycle Assessment (LCA) tools.

Scoring tools, such as BREEAM (BRE 2017) and LEED (USGBC 2017), are based on a multi-criteria assessment. The methodology consists of associating scores to a number of criteria and calculating a weighted sum to obtain a single overall score. These tools cover a wide range of sustainability issues such as energy use, material use, water use, user transport and comfort. Methods are available for an evaluation at various scale levels, ranging from individual buildings to neighbourhoods.

LCA tools, such as the Athena impact estimator for buildings (Athena Sustainable Materials Institute 2017) and Elodie (CSTB 2017), use a life cycle approach which evaluates the environmental impacts generated during the entire building life span. Although LCA tools are preferred above scoring tools because of their scientific base (Trusty and Horst 2002), there are two important limitations. First, most LCA tools are limited to the building level. Only a few tools, such as novaEQUER (IZUBA énergies 2017), consider the neighbourhood scale level. Second, current LCA tools only cover the environmental dimension of sustainability, neglecting economic, social and quality aspects. These limitations need to be overcome to make LCA tools competitive with the currently widely used scoring tools.

1.2 Objectives

The main objective of this research is to develop a method to assess the sustainability of neighbourhoods, using an integrated life cycle approach. This method should combine an assessment of the economic, environmental and social performance of neighbourhoods, together with an assessment of the neighbourhood qualities (Figure 1.1). The assessment of the economic and environmental performance consists of the calculation of the life cycle financial and environmental impact based on respectively Life Cycle Costing (LCC) and Environmental Life Cycle Assessment (E-LCA). As Social Life Cycle Assessment (S-LCA) is still under development (Sala et al. 2015), the social performance is evaluated as part of the quality assessment which is based on a Multi-Criteria Analysis (MCA). Despite the importance of all evaluation aspects, this PhD thesis is mainly focussing on the assessment of the economic and environmental performance. The assessment of the qualities (together with the social performance) is rather elaborated conceptually.

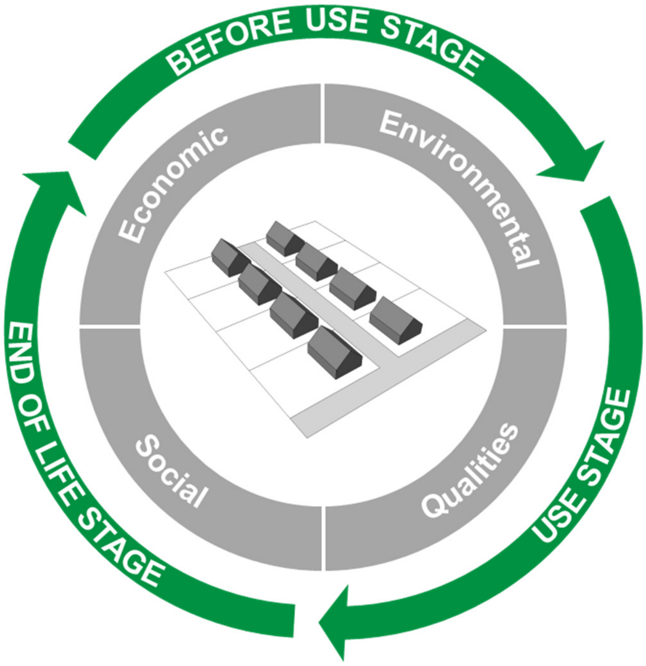

Figure 1.1: Main research objective – elaboration of an assessment method for the evaluation of sustainability in neighbourhoods, based on an integrated life cycle approach.

The focus of this research is on newly built residential neighbourhoods. The method is nevertheless extendable for the assessment of mixed use neighbourhoods and refurbishment projects. Furthermore, the approach is elaborated for the Belgian context but can be applied to other contexts.

The method developed can be used as a decision support tool, helping decision makers, such as architects, urban planners, engineers and public authorities, to improve the sustainability of neighbourhoods. Moreover the method is applicable during the different design stages so that designers can improve their design from the first design phase onwards when most important decisions are taken.

This main objective leads to two sub-objectives. The first is to extent the scale of the individual building to clusters of buildings and neighbourhoods. As a building is never a stand-alone object but interacts with the surroundings, it is important to consider the influence of urban planning decisions on the amount of necessary infrastructure and open spaces. The first aim is therefore to extend the life cycle methodology from individual buildings to the neighbourhood scale, by including the impact of infrastructure and open spaces (Figure 1.2).

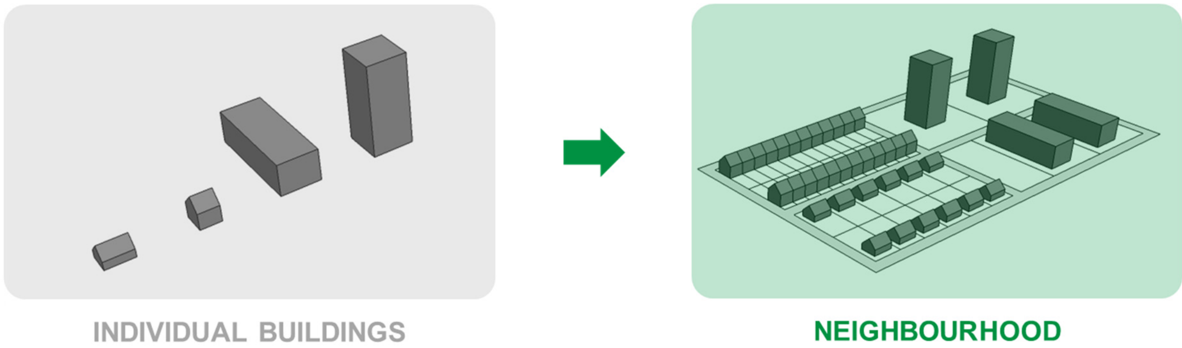

Figure 1.2: Sub-objective 1- extension to the neighbourhood scale level.

The second sub-objective is to extend the evaluation scope in order to include aspects influenced by decisions taken at the neighbourhood scale level. For example, the heating energy use in neighbourhoods might be affected by shading effects caused by interacting buildings. Another example is the influence of neighbourhood characteristics, such as accessibility, public transport and cycling infrastructure, on the impact of user transport. In this research five main aspects[2] are elaborated in detail: operational energy use, operational water use, primary land use[3], user transport and neighbourhood qualities (Figure 1.3).

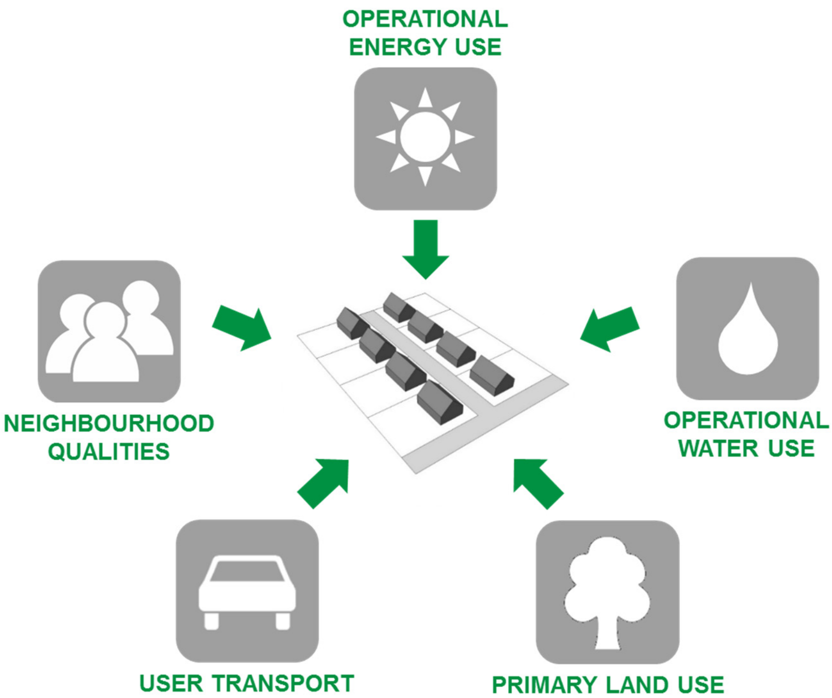

Figure 1.3: Sub-objective 2- extension of the evaluation scope.

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[2] These five main aspects are identified based on the literature review of existing BSA tools (see Chapter 2). While these aspects are mostly assessed in scoring tools, they are only partially or not included in LCA tools.

[3] Neighbourhoods are responsible for two types of land use interventions: primary land use, i.e. the neighbourhood spatial footprint and secondary land use, associated with the resource extraction, production, transport and end-of-life treatment of construction products (Allacker et al. 2014) but also the operational energy use, operational water use and user transport. This is further elaborated in Chapter 5.

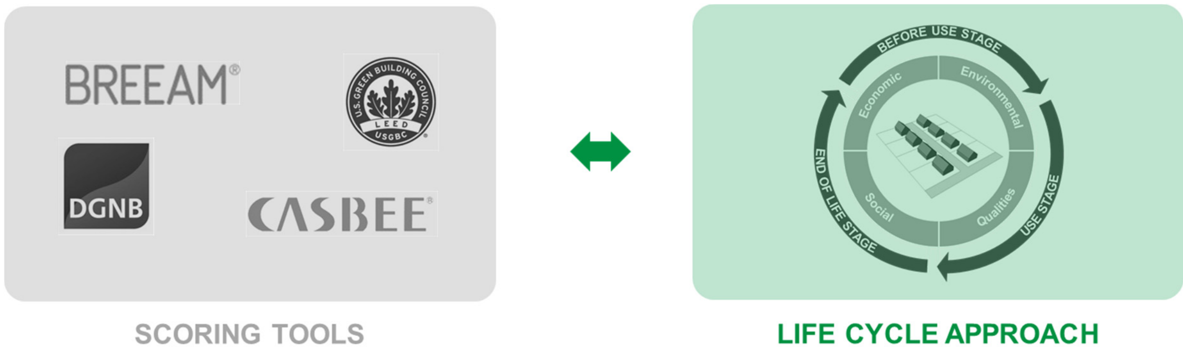

Figure 1.4: Side-objective - comparison between the integrated life cycle approach and scoring tools.

A side-objective is to make a comparison between a number of well-known scoring tools for neighbourhoods and the developed integrated life cycle approach (Figure 1.4). Based on four schematic neighbourhood models, the life cycle impacts and qualities resulting from various sustainability measures are evaluated and compared with the scores awarded in scoring tools. Based on this comparison, convergences and divergences are highlighted and recommendations for methodological improvements are formulated. This analysis will contribute to advanced transparency among the variety of available scoring tools, which are often characterized by their black box nature.

1.3 Research questions

Concerning the main objective, this research aims at addressing the following research questions:

- How can neighbourhoods be modelled within an integrated life cycle approach?
- What is the impact of urban planning interventions on the sustainability of neighbourhoods?

Regarding the side-objective, the following research question is addressed:

- How effective are scoring tools to improve the life cycle impacts and qualities of neighbourhoods?

1.4 Outline of the research

This PhD thesis is subdivided in 10 chapters:

- Chapter 1: Introduction

  The first chapter describes the background of the research, the objectives, research questions and the outline of the dissertation.

- Chapter 2: Existing Building Sustainability Assessment tools for neighbourhoods

  This chapter provides a literature review of existing BSA tools for neighbourhoods. An evaluation framework is proposed to compare the various tools and highlight their strengths and weaknesses.

- Chapter 3: Integrated life cycle approach

  In the third chapter the integrated life cycle approach is presented, including the assessment of the economic, environmental and social performance and the quality assessment.

- Chapter 4: Extension to the neighbourhood scale level

  Chapter 4 focuses on the extension from the building to the neighbourhood scale level. A hierarchical evaluation structure based on the element method for cost control is proposed.

- Chapter 5: Extension of the evaluation scope

  This chapter describes the extension of the evaluation scope, focusing on methodological aspects related to the assessment of operational energy use, operational water use, primary land use, user transport and neighbourhood qualities.

- Chapter 6: Calculation model

  In the sixth chapter the structure of the calculation model is elaborated. The existing building calculation model and the extension of this model to assess neighbourhoods are described.

- Chapter 7: Assessment of networks and open spaces

  Chapter 7 consists of the analysis of a number of neighbourhood elements. The financial and environmental impacts of networks, such as road infrastructure and utilities, and open spaces, such as squares and green areas, are described.

- Chapter 8: Assessment of schematic neighbourhood models

  In this chapter four schematic neighbourhood models with diverse built densities and layouts are assessed to investigate the influence of urban planning on the financial and environmental impacts of neighbourhoods. For each neighbourhood model, the impact of material use, operational energy use, operational water use, primary land use and user transport is analysed in detail.

- Chapter 9: Comparison between the scoring tools and the life cycle approach

  Chapter 9 focuses on the comparison between a number of scoring tools for the evaluation of neighbourhoods and the integrated life cycle approach developed in this research. For each of the analysed schematic neighbourhood models, the life cycle impacts and qualities resulting from various sustainability measures are compared with the scores awarded in scoring tools.

- Chapter 10: Conclusions

  In the last chapter main conclusions and recommendations for further research are formulated.

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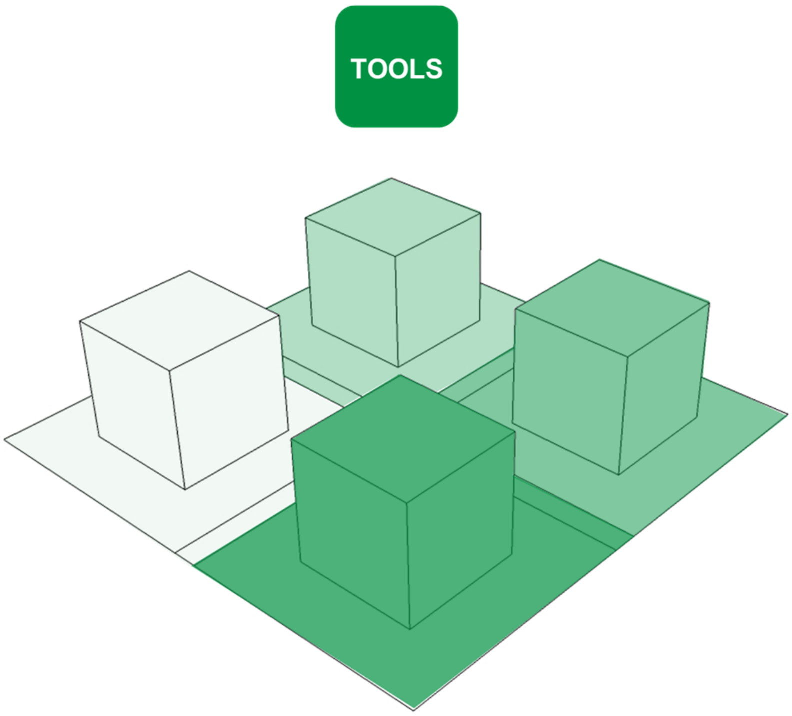
CHAPTER 2

Existing Building Sustainability Assessment tools for neighbourhoods

This chapter consists of a literature review of seven existing Building Sustainability Assessment (BSA) tools for neighbourhoods, including both scoring and Life Cycle Assessment (LCA) tools. The tools are analysed based on an evaluation framework focussing mainly on the methodological aspects. Based on this analysis, the strengths and weaknesses are identified and recommendations for improvement are formulated.

This literature review is published as part of a book section in “Architecture and Sustainability: Critical Perspectives for Integrated Design”(Trigaux et al. 2015). As new versions of the analysed tools are now available, the data are updated. Furthermore the sustainability assessment tool for neighbourhoods “Duurzaamheidsmeter wijken”(Flemish Government 2017), recently developed by the Flemish administration, is also included in the analysis.



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2.1 Tool classification

Various classifications exist for the multitude of BSA tools that have been developed. Some classifications are based on the method used (e.g. classification in the IEA annex 31), others on the tool purpose (e.g. the ATHENA classification) or on the data used (quantitative versus qualitative data) (Forsberg and von Malmborg 2004; Haapio and Viitaniemi 2008). As this study focuses on methodological aspects, the IEA classification is selected, which distinguishes five classes of tools (IEA Annex 31 2004):

1. Energy Modelling Software
2. Environmental LCA Tools for Buildings or Building Stocks
3. Environmental Assessment Frameworks and Rating Systems
4. Environmental Guidelines or Checklists for Design and Management of Buildings
5. Environmental Product Declarations, Catalogues, Reference Information, Certifications and Labels

Some tools (classes 1, 4 and 5) can only be used as informative and supporting tools and not for assessing the sustainability of a building or neighbourhood. The comparative analysis of BSA tools in this dissertation is hence limited to the LCA (class 2) and scoring tools (class 3).

Scoring tools can be subdivided in first generation and second generation assessment tools (Ebert et al. 2011). The first generation tools, such as BREEAM (BRE 2017), mainly focus on environmental and energy-related criteria (even if economic and social criteria are also included). The more recent second generation tools, such as DGNB (DGNB GmbH 2017), consider a subdivision into the three main dimensions of sustainability (i.e. economic, environmental and social) and integrate a number of criteria based on Environmental Life Cycle Assessment (E-LCA) and Life Cycle Costing (LCC). The comparative analysis in this chapter includes both the first and second generation scoring tools[1].

2.2 Evaluation framework

For the comparative analysis of the BSA tools, an evaluation framework has been developed, based on a literature review of existing comparative studies (Reijnders and van Roekel 1999; Forsberg and von Malmborg 2004; Haapio and Viitaniemi 2008; Allacker 2010; Vandevyvere 2010; Ebert et al. 2011; Reed et al. 2011). Those studies however mainly focus on one specific IEA class or on tools for assessment at the building level.

The structure of the evaluation framework is based on the framework of Baumann and Cowell for comparing different environmental management approaches (Baumann and Cowell 1999).

[1] The distinction between first and second generation tools should not be interpreted too strictly as some tools could be classified in both categories. For example, the most recent version of CASBEE for Urban Development (IBEC and JSBC 2014) is subdivided into economic, environmental and social criteria but does not include criteria based on E-LCA and LCC.

Their framework consists of two major dimensions. The contextual dimension focuses on the situation in which the method is used. The methodological dimension – through the breakdown of the method to its constituent parts - allows to identify aspects shared (or not) by the different methods. As these two aspects are also crucial for a better understanding and appropriate use of BSA tools, the same subdivision is used, considering following sub-aspects:

- Contextual aspects: country, developer, tool status and overall purpose;
- Methodological aspects: evaluation scope, evaluation structure, investigated dimensions, indicators, aggregation and weighting, and format of the results.

2.3 Selection of tools for the comparative analysis

For the comparative analysis seven BSA tools for neighbourhoods have been selected, covering class 2 and 3 from the IEA classification:

- First generation scoring tools: BREEAM Communities (version 2012) (BRE 2016), CASBEE for Urban Development (version 2014) (IBEC and JSBC 2014) and the Flemish tool "Duurzaamheidsmeter Wijken", further referred to as "DZM Wijken"(Flemish Government 2017);
- Second generation scoring tools: DGNB New Urban Districts (version 2012) (DGNB GmbH 2012)[2] and the method developed by Vandevyvere ("Strategies Towards Increased Sustainable Building in Flanders – Application on the Scale of the Urban Fragment") (Vandevyvere 2010);
- LCA tools: GreenCalc+[3] (Stichting Sureac 2013) and novaEQUER (IZUBA énergies 2017).

The selection was based on the representativeness for the methods in the specific IEA class and/or on their usefulness in the Belgian context. The selection does not reflect any preference between existing tools. Although LEED (USGBC 2017) is also a widely used tool, it was not considered as it is methodologically very similar to BREEAM but less adapted to the European context.

2.4 Comparative analysis of the selected tools

Table 2.1 provides an overview of the results of the comparative analysis. The main differences are summarised in the subsequent paragraphs.

[2] Recently, an updated German version of DGNB New Urban Districts has become available (DGNB GmbH 2016). As there is no reference to this new version on the English DGNB webpage (DGNB GmbH 2017), a previous version (2012) is used in this research.

[3] The development of GreenCalc+ has been stopped after the publication of this literature review in (Trigaux et al. 2015). However, as this LCA tool is interesting from a research point of view, it is still included in the comparative analysis.

A first important difference in the analysed tools is their purpose. While scoring tools focus on the calculation of an overall (single) sustainability score, LCA tools provide quantitative environmental impact results as decision support. The scoring tools are hence rather communication/labelling tools while the LCA tools are rather analytical/design tools. However, this is not a strict distinction as both tools contribute to both goals.

Within the analysis of the scope, the scale and time span have been compared. The scale coverage of the LCA tools ranges from small (i.e. group of buildings) to large scale developments. The scoring tools on the other hand are mostly related to the medium and large scale level. The evaluation of individual buildings and small scale developments requires the use of specific scoring tools with appropriate criteria and scores. Regarding the time span, only the second generation scoring tools and the LCA tools consider the whole life cycle of the neighbourhood.

Thirdly, the tools differ in evaluation structure. The LCA tools use a detailed modelling of the neighbourhood based on a subdivision in constituting elements and hierarchic scale levels. In scoring tools no modelling step is required and the evaluation is based on a subdivision in thematic categories, each covering a subset of criteria.

Regarding the investigated sustainability dimensions, scoring tools cover the three pillars of sustainability and assess a number of qualities (i.e. functional, technical, site and process qualities). How these are combined depends on the tool: quality criteria are either mixed with the other sustainability criteria (e.g. BREEAM Communities) or evaluated in separate categories (e.g. second generation scoring tools). The LCA tools on the other hand are limited to the evaluation of the environmental dimension, focussing on global/ regional environmental impacts. Local impacts such as local pollution and disturbances are not or only partially assessed.

Various indicators are used to assess the different sustainability dimensions. Compared to the purely quantitative indicators in the LCA tools, scoring tools consist of a mix of quantitative and qualitative indicators based on guidelines and checklists (in some cases combined with life cycle data such as in the second generation scoring tools).

In order to combine the different indicator-results into an overall (single) sustainability-score, an aggregation step is needed. All scoring tools calculate such an overall score by applying weighting factors to the individual indicators based on the judgement of expert and stakeholder panels. The LCA tools, on the other hand, do not always aggregate the individual indicator results.

Finally, the scoring tools express the assessment results in an overall rating (e.g. excellent, good, pass) while the LCA tools provide the total impact data and are hence more transparent (e.g. life cycle CO_2 equivalents, life cycle environmental cost). Different types of charts are used to present the results in more detail (e.g. results for the individual indicators, contribution of the life cycle stages).

Table 2.1: Comparison of BSA tools for neighbourhoods.

	Scoring tools					LCA tools	
	BREEAM Communities	CASBEE for Urban Development	DZM Wijken	DGNB New Urban Districts	Strategies Sustainable Building Flanders	GreenCalc+	novaEQUER
Contextual aspects							
Country	UK	Japan	Belgium	Germany	Belgium	The Netherlands	France
Developer	BRE Group	JSBC and IBEC	Flemish administration	DGNB	Vandevyvere H. - KU Leuven	Stichting Sureac	IZUBA énergies and Mines Paris Tech
Status	Market-oriented tool	Market-oriented tool	Governmental tool	Market-oriented tool	Research tool	Market-oriented tool	Market-oriented too
Overall purpose	Communication / labelling	Communication / labelling	Communication / labelling	Communication / labelling	Communication / labelling	Analytical / design tool	Analytical / design tool
Methodological aspects							
Evaluation scope							
Object analysed	Moderate to large scale development	Single block to district scale	(Part of) neighbourhood – scale not defined	Medium to large scale development (minimum 2ha)	Urban fragment – scale not defined	Small to large scale development	Small to large scale development
Function of buildings	Mixed use	Mixed use	Mainly residential	Mixed use	Mainly residential	Mixed use	Mixed use
Refurbishment?	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Life cycle stages	No life cycle evaluation[4]	No life cycle evaluation[5]	No life cycle evaluation[6]	Life cycle of 50 years (from production to EOL)	Life cycle of 60 years (from production to EOL)	Life cycle of 75 years (from production to EOL)	Life span adaptable (from production to EOL)

[4] The life cycle impact of building materials is evaluated indirectly based on the environmental profiles in the Green Guide to Specification.

[5] Only the CO2 emissions associated with energy use from traffic and buildings and CO2 absorption from green areas are calculated.

[6] The impact of building materials can be evaluated based on LCA or on qualitative criteria.

	Scoring tools					LCA tools	
	BREEAM Communities	CASBEE for Urban Development	DZM Wijken	DGNB New Urban Districts	Strategies Sustainable Building Flanders	GreenCalc+	novaEQUER
Evaluation structure	6 criteria categories: - Governance - Social and economic wellbeing - Resources and energy - Land use and ecology, - Transport and movement - Innovation Criteria assigned to 3 process steps[7]	2 main criteria categories: - Environmental Quality (Q) – including 3 major items (Environment, Society and Economy), further divided in middle, small and minor items - Environmental Load (L) – based on the level of reduction in CO2 emissions	9 criteria categories (divided in subcategories): - Quality control - Well-being & welfare - Mobility - Physical environment - Green & nature development - Water - Materials and waste - Energy - Innovation Criteria assigned to 2 process steps[8]	5 criteria categories (divided in subcategories): - Ecological - Economic - Sociocultural and functional - Technical - Process	3+1 criteria categories: - Ecological - Sociocultural - Economic - Process (transversal category)	Subdivision in scale levels: - Neighbourhood - Buildings - Building elements 4 modules: - Material - Energy - Water - Mobility	Subdivision in scale levels: - Neighbourhood - Buildings - Building elements
Investigated dimensions							
Economic	Local economy	Local economy	Financial feasibility, local economy	Life cycle costs, value stability, local economy	Life cycle costs, value stability, local economy, juridical security	No economic assessment	No economic assesment

[7] The following master planning steps are considered: "Step 1: Establishing the principle of development", "Step 2: Determining the layout of the development"' and "Step 3: Designing the details".

[8] The following master planning steps are considered: "Location choice" and "Design stage".

	Scoring tools					LCA tools	
	BREEAM Communities	CASBEE for Urban Development	DZM Wijken	DGNB New Urban Districts	Strategies Sustainable Building Flanders	GreenCalc+	novaEQUER
Environmental	Material, energy, water, user transport, site land use	Material, energy, water, user transport, site land use, operational waste	Material, energy, water, user transport, site land use, operational waste, food production	Material, energy, water, user transport, site land use, operational waste, food production	Material, energy, water, user transport, site land use, operational waste	Material, energy, water, user transport	Material, energy, water, user transport, site land use, operational waste
	Local impacts: pollution and disturbances	Local impacts: pollution and disturbances	Local impacts: pollution and disturbances	Local impacts: pollution and disturbances	Local impacts: pollution and disturbances	Local impacts: disturbances	Local impacts: odour
Social	Identity, diversity, inclusivity, sociability, spatial quality	Identity, diversity, inclusivity, spatial quality	Diversity, inclusivity, sociability, social entrepreneurship, spatial quality	Identity, diversity, inclusivity, sociability, spatial quality	Identity, diversity, inclusivity, sociability, spatial quality	No social assessment	No social assessment
Qualities	Functional, technical, site and process qualities	Functional, technical, site and process qualities	Functional, technical, site and process qualities	Functional, technical, site and process qualities	Functional, technical, site and process qualities	No quality assessment	No quality assessment
Indicators	Quantitative and qualitative indicators based on guidelines and checklists	Quantitative and qualitative indicators based on guidelines and checklists	Quantitative and qualitative indicators based on guidelines and checklists	Quantitative and qualitative indicators based on LCA, guidelines and checklists	Quantitative and qualitative indicators based on LCA, guidelines, checklists and expert judgement	Quantitative LCA indicators[9]	Quantitative LCA indicators[10]

[9] Impact categories are subdivided in four areas: emissions, resource depletion, land use and disturbances.

[10] 12 impact categories are considered: primary energy use, inert waste, radioactive waste, global warming, abiotic depletion of resources (non-renewable), odour, water use, photochemical ozone formation, human toxicity, eco-toxicity (marine), eutrophication and acidification.

	Scoring tools					LCA tools	
	BREEAM Communities	CASBEE for Urban Development	DZM Wijken	DGNB New Urban Districts	Strategies Sustainable Building Flanders	GreenCalc[+]	novaEQUER
Aggregation/ weighting	Weighting to an overall score in 2 steps (criteria and categories) Weighting factors based on expert panel	Environmental quality (Q): weighting to an overall score in 5 steps (criteria, minor, small, middle and major items) No information on weighting factor definition	Weighting to an overall score in 3 steps (criteria, subcategories and categories) Weighting factors based on expert panel	Weighting to an overall score in 2 steps (criteria and categories) No information on weighting factor definition	Weighting to an overall score in 1 or 2 steps (when subdivision of criteria in sub criteria) Weighting factors based on expert panel	Valuation of environmental impacts (prevention cost method)	No weighting
Format of the results	Rating on a scale from Pass, Good, Very Good, Excellent and Outstanding	- Rating on a scale from class C (poor), B-, B+, A to S (excellent) - Building Environmental Efficiency score (BEE) = Quality (Q)/ Load (L), displayed in an X/Y diagram - Bar chart with CO2 emissions - Radar and bar charts with major and middle item results	- Rating on a scale from Pass, Good, Very Good, Excellent and Outstanding - Radar chart with categories results	- Rating on a scale from Bronze, Silver to Gold - Radar chart with detailed criteria results	- Overall Score (%) - Radar chart with detailed criteria results	- Environmental costs - Environmental index: comparison with a self-defined reference neighbourhood - Bar chart with all impact indicator results	Bar and radar chart with all impact indicator results

2.5 Strengths and weaknesses of the selected tools

The comparative analysis allows to identify the strengths and weaknesses in the BSA tools and to formulate recommendations to overcome the weaknesses. Firstly, the scoring tools are more user-friendly compared to LCA tools which deal with a huge amount of data. In consequence, the use of a well-structured evaluation model, i.e. a subdivision in scale levels and constituting elements, is recommended for LCA tools to deal with this complexity.

Secondly, scoring tools are more comprehensive than LCA tools as the former cover a wide range of sustainability issues while LCA tools focus on the environmental dimension solely. The wide scope of scoring tools is however not evaluated based on a scientific and systematic study of impacts (Reijnders and van Roekel 1999). An LCA study of the LEED criteria for example revealed discrepancies between the rating levels and their actual environmental impact (Humbert et al. 2006). Current scoring systems are hence not adapted to estimate the relative improvement associated with specific changes in design and would therefore not guarantee sustainable decision taking (Reijnders and van Roekel 1999). There is moreover a risk that designers are driven by scoring points and not by sustainability (Reed et al. 2011).

It is therefore recommended that future LCA tools broaden their scope to cover also economic, social and quality aspects. For the scoring tools we recommend to adapt the current non-scientifically based assessment to a more consistent evaluation system that guarantees sustainability. By integrating life cycle evaluation (LCC and E-LCA) in their criteria, second generation scoring tools increased their robustness and transparency but the translation of the LCC and E-LCA results to scores, weighted with other quantitative and qualitative criteria, remains questionable.

2.6 Conclusions

In this chapter seven BSA tools for neighbourhoods (i.e. scoring tools and LCA tools as classified in the IEA Annex 31) are compared and their strengths and weaknesses are highlighted. Although scoring tools are more user-friendly and cover a wider range of sustainability issues, these are found not sufficiently robust to support sustainable decision taking. A more consistent quantitative approach based on life cycle thinking is preferred as applied in LCA tools.

To increase the usefulness of LCA tools along the design process, those tools should allow for various levels of simplification and accuracy, i.e. from screening LCA to complete LCA, such as recommended by the EeBGuide Guidance Document (European Commission 2017). Furthermore, the comprehensiveness of LCA tools should be improved by including economic, social and quality aspects. First, economic and social aspects should be assessed, using standardised methods such as LCC and Social Life Cycle Assessment (S-LCA)[11]. Second, quality

[11] As mentioned in Chapter 3, S-LCA is still under development (Sala et al. 2015) and therefore not mature enough to be integrated in LCA tools.

assessment should be included, maintaining a clear distinction between the quality score (based on qualitative data) and the life cycle impacts (based on quantitative data).

An example of such approach is the method developed in the SuFiQuaD research project ("Sustainability, Financial and Quality Evaluation of Dwelling Types") (Allacker 2010; Allacker et al. 2013). This method was however not discussed in the comparative analysis as it is limited to evaluations at the building level. In this dissertation the SuFiQuaD method is used as a starting point to upscale the LCA methodology to the neighbourhood scale level as it fulfils the recommendations formulated above.

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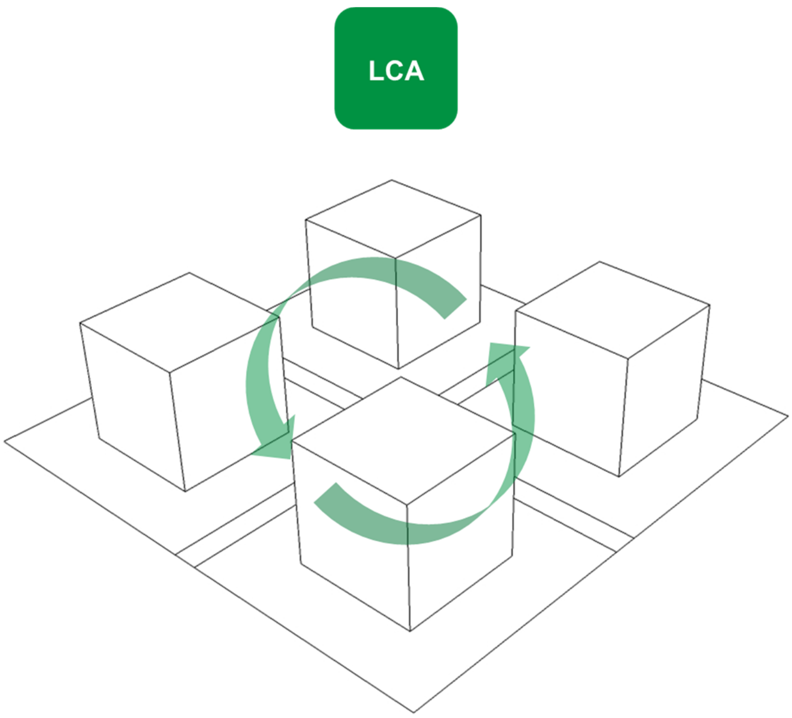
CHAPTER 3

Integrated life cycle approach

In this chapter the integrated life cycle approach for neighbourhoods is described. This approach combines an assessment of the economic, environmental and social performance, together with an assessment of the neighbourhood qualities. The proposed approach is based on an existing assessment method for buildings developed in the SuFiQuaD research project (Allacker 2010; Allacker et al. 2013a). After a description of the global structure, the methodological aspects related to the assessment of the economic, environmental and social performance and the quality assessment are presented. Finally an overview is given of the analysed life cycle stages and system boundaries.



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3.1 Global structure of the assessment method

The sustainability assessment method for neighbourhoods elaborated in this research is based on an existing assessment method for buildings developed in the SuFiQuaD research project ("Sustainability, Financial and Quality evaluation of Dwelling Types") (Allacker 2010; Allacker et al. 2013a). This four-year research project was financed by the Belgian Science Policy Office (BELSPO) and realized by a research consortium of KU Leuven, the Flemish Institute for Technological Research (VITO) and the Belgian Building Research Institute (BBRI).

In the SuFiQuaD method a distinction is made between the assessment of the building impact and the building qualities (Figure 3.1). First, the building impact includes an evaluation of the economic and environmental performance based on a life cycle methodology. This consists of an assessment of the financial cost and environmental impact of buildings using respectively Life Cycle Costing (LCC) and Environmental Life Cycle Assessment (E-LCA). Second, building qualities are evaluated based on a Multi-Criteria Analysis (MCA). The following qualities are assessed: dimensional characteristics, functional characteristics, technical characteristics and qualities related to the surroundings of the dwelling. The quality assessment is necessary to ensure that the reduction of the financial and environmental impact is not to the detriment of the provided building qualities. Striving for sustainable buildings should therefore focus on a balance between minimisation of the building financial and environmental impact and maximisation of the building qualities.

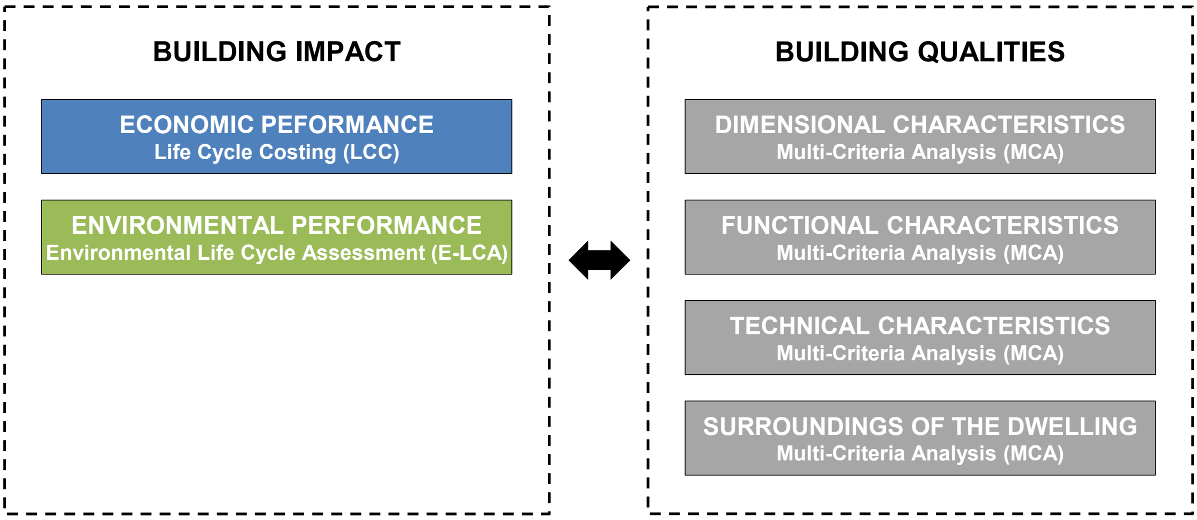

Figure 3.1: Global structure of the SuFiQuaD method.

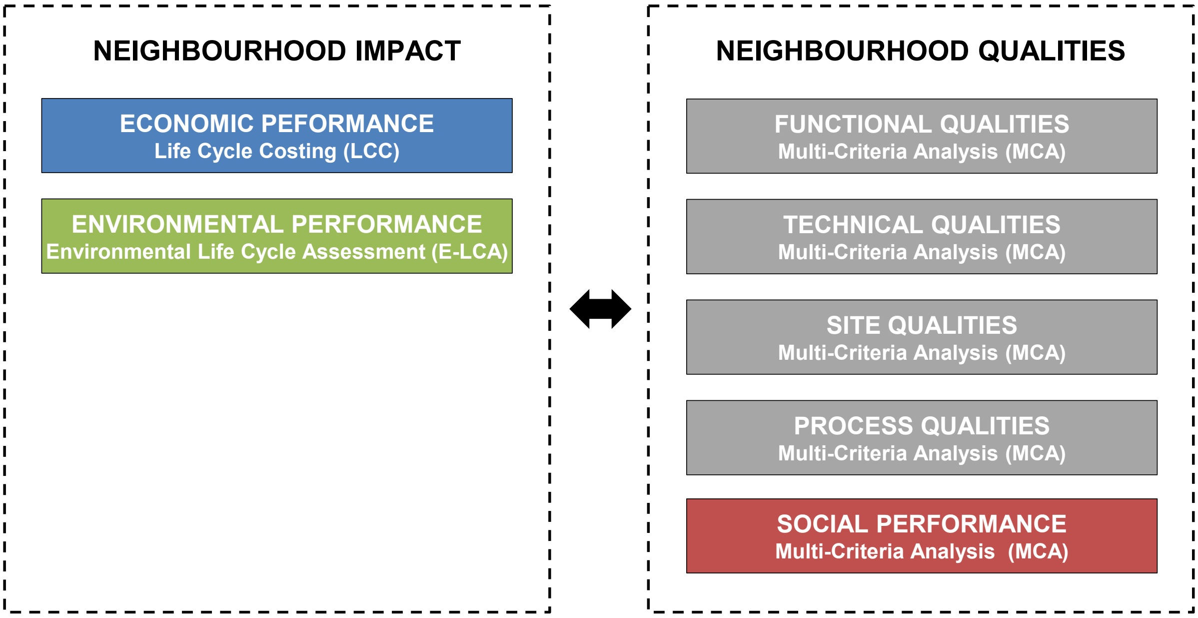

Figure 3.2: Global structure of the integrated life cycle approach for neighbourhoods.

In this research the structure of the SuFiQuaD method is used as a starting point, with a distinction between the neighbourhood impact and the neighbourhood qualities (Figure 3.2). Compared to the original method, several adaptations are made. First, an assessment of the social performance is added in order to cover all three dimensions of sustainability (i.e. economic, environmental and social dimension). As further explained in section 3.4, the social performance is assessed as part of the quality assessment, as social Life Cycle Assessment (S-LCA) is still under development (Sala et al. 2015). Second, the structure of the quality assessment is adapted to include additional quality aspects, such as site and process qualities[1].

3.2 Assessment of the economic performance

In accordance with the European standards EN 16627 (CEN 2015), the assessment of the economic performance is based on the LCC approach. The LCC approach considers the financial cost during the whole life span of the neighbourhood. These include the investment cost, the cost during the use stage and the cost at the end of the neighbourhood life cycle. A detailed description of the LCC method used in this research can be found in the publications of the SuFiQuaD project (Allacker 2010; Allacker et al. 2013a).

The assessment is conducted from the perspective of the neighbourhood user or inhabitant. Regarding the cost allocation, a distinction is often made between private costs related to buildings and gardens, which are carried by the neighbourhood inhabitants, and public costs related to infrastructure and public open spaces, which are allocated to the municipality. This

[1] Process qualities are qualities related to the neighbourhood development process and governance, such as the planning, quality control and participation of stakeholders (Chapter 5).

distinction is however not used in this research[2] as it is assumed that from a sustainability perspective public costs should be indirectly assigned to the users or inhabitants via fees and taxes.

Furthermore, it is assumed that all construction, maintenance and cleaning activities are carried out by professionals. Self-build, cleaning and maintenance by the neighbourhood inhabitants, which can considerably reduce the financial cost, are not considered in this research.

In the subsequent paragraphs, an overview is given of the financial data, the calculation of the present value of future costs and the economic parameters used in this research.

3.2.1 Financial data

The financial data are collected from various sources. Concerning the building elements, the financial data are mainly based on the Belgian cost database ASPEN (ASPEN 2015a; ASPEN 2015b), combined with product specific data. The ASPEN database contains cost data for new construction, refurbishments but also demolition activities. For the cleaning and maintenance processes, the cost data used in the SuFiQuaD project (Allacker 2010; Allacker et al. 2013a), have been updated to a nominal value for the year 2015 based on the ABEX index (ABEX 2017), which reflects the evolution of the construction prices in Belgium.

For the neighbourhood infrastructure, the British Spon's Price Books "External works and landscape price book" (Spon press 2015a) and "Civil engineering and highway works price book" (Spon press 2015b), are used as a Belgian cost database is lacking. In these books cost data are reported as net prices (in British pound) excluding overhead and profit. An addition of 5% to 10% and 5% to 15% onto net turnover is suggested for respectively overhead and profit (Spon press 2015b). In this research an average add-on of respectively 7.5% and 10% is applied, which results in a total add-on of 17.5%. For the conversion from pound to euro, a conversion rate of 1 pound equals 1.38 euro is assumed, which corresponds to the average exchange rate of 2015 (European Central Bank 2017).

Regarding the removal of construction and demolition waste, cost data per waste category from the SuFiQuaD project are used (Allacker 2010; Allacker et al. 2013a). The prices have been updated to a nominal value for the year 2015 based on the ABEX index (ABEX 2017).

3.2.2 Present value of future costs

The standard approach in economics to deal with future costs is to calculate their present value so that future costs can be compared with present costs (De Troyer 2007). The present value of future costs is calculated based on Formula [3.1] (De Troyer 2007; Allacker 2010):

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[2] The modular structure of the assessment method based on a subdivision in functional elements (see Chapter 4) however allows to make a clear distinction between public and private costs.

$$PV[C_t] = C_0\left(\frac{1+g}{1+d}\right)^t \qquad [3.1]$$

With:

- $PV[C_t]$ = present value of a cost in year t (euro)
- C_0 = cost for the year of reference (euro)
- g = nominal growth rate
- d = nominal discount rate

The nominal growth rate (g) reflects the price evolution of products or services over time. The nominal discount rate (d) takes into account the fact that the amount of money needed for future cash flows can have been invested in the meantime. When the discount rate is greater than zero, a lower value is attributed to future costs compared to present costs (Allacker 2010). In this dissertation the present value of all future costs is calculated for the reference year 2015, which is assumed to be the construction year of the neighbourhood[3].

To take into account the impact of inflation, the nominal rates are often translated to real rates using Formulas [3.2] and [3.3] (Allacker 2010):

$$1+g' = \frac{1+g}{1+i} \qquad [3.2]$$

$$1+d' = \frac{1+d}{1+i} \qquad [3.3]$$

With:

- g' = real growth rate
- d' = real discount rate
- i = inflation rate

Based on the real growth and discount rates, Formula [3.1] can then be written as follows:

$$PV[C_t] = C_0\left(\frac{1+g'}{1+d'}\right)^t \qquad [3.4]$$

3.2.3 Economic parameters

The economic parameters used in this research are summarized in Table 3.1. The parameters are based on Belgian statistical data and correspond with the basic scenario defined in the SuFiQuaD project (Allacker 2010). The real discount and growth rates are calculated assuming

[3] In practice, the construction of neighbourhoods is a process that can last many years. In this research, a single year is however assumed for all construction works.

a general inflation rate of 2%, which is in line with the current Belgian statistics on inflation (Belgian Federal Government 2017).

In contradiction to the European standards (CEN 2015), taxes such as VAT are included in the LCC calculations in order to take into account the different rates that are applicable depending on the type of construction activity. Based on the current Belgian situation, a VAT rate of 21% is applied for the construction of new buildings and 6% for refurbishments, replacements and maintenance activities. For the neighbourhood infrastructure a fixed VAT rate of 21% is assumed for all life cycle costs. Concerning energy and water use, VAT rates of respectively 21% and 6% are applied.

Table 3.1: Economic parameters applied for the financial and environmental costs (real rates above the inflation), based on (Allacker 2010).

	Financial costs	**Environmental costs**
Real discount rate	2%	0%
Real growth rate material and water	0%	0%
Real growth rate labour	1%	-
Real growth rate energy	2%	0%

3.3 Assessment of the environmental performance

In accordance with the European standards EN 15978 (CEN 2011), the assessment of the environmental performance is based on the E-LCA approach, which considers the environmental impacts generated during the whole life span of the neighbourhood. In this dissertation the environmental impact assessment is based on the E-LCA method developed within the MMG research project ("Environmental profile of building elements"), commissioned by the Public Waste Agency of Flanders (Allacker et al. 2013b; De Nocker and Debacker 2015). This E-LCA method is an update of the E-LCA method developed in the SuFiQuaD project, in order to be in line with recent E-LCA standards and guidelines in Europe (CEN 2011; EC-JRC 2011; CEN 2013). An overview of the environmental data used and related indicators is provided in the subsequent paragraphs.

3.3.1 Environmental data

The Swiss Ecoinvent database (version 2.2)[4] is used for the Life Cycle Inventory (LCI) (Frischknecht et al. 2007). Preference is given to Western European processes to ensure the representativeness for the Belgian context. When generic Western European processes are lacking, Swiss data records are adapted by replacing the Swiss electricity mix and transport

[4] The MMG E-LCA data have been recently updated to Ecoinvent version 3. However, due to time constraints, the original data from Ecoinvent version 2.2 are still used in this PhD dissertation.

processes by European corresponding processes, assuming that construction products on the Belgian market are made within Belgium and neighbouring countries (Allacker et al. 2013b).

For specific materials, such as concrete and road asphalt, new records were defined by modifying the quantities and/or underlying processes in existing similar records.

3.3.2 Environmental impact categories

The environmental impact categories used in the MMG E-LCA method include the ones required by the EN 15804+A1 standard (CEN 2013), which are further referred to as CEN indicators (Table 3.2). In addition, seven more impact categories are considered based on the International Reference Life Cycle Data System (ILCD) Handbook (EC-JRC 2011). The additional impact categories are further referred to as CEN+ indicators (Table 3.3).

Table 3.2: CEN indicators and corresponding impact assessment models (De Nocker and Debacker 2015).

CEN indicator	**Impact assessment model**
Global warming	EN 15804+A1 (CEN 2013)
Ozone depletion	EN 15804+A1 (CEN 2013)
Acidification of soil and water	EN 15804+A1 (CEN 2013)
Eutrophication	EN 15804+A1 (CEN 2013)
Photochemical ozone creation	EN 15804+A1 (CEN 2013)
Depletion of abiotic resources - elements	EN 15804+A1 (CEN 2013)
Depletion of abiotic resources - fossil fuels	EN 15804+A1 (CEN 2013)

Table 3.3: CEN+ indicators and corresponding impact assessment models (De Nocker and Debacker 2015).

CEN+ indicator	**Impact assessment model**
Human toxicity - cancer effects	(Rosenbaum et al. 2008)
Human toxicity - non-cancer effects	(Rosenbaum et al. 2008)
Particulate matter	(Rabl and Spadaro 2004)
Ionising radiation - human health	(Frischknecht et al. 2000)
Ionising radiation - ecosystems	(Garnier-Laplace et al. 2009)
Ecotoxicity - freshwater	(Rosenbaum et al. 2008)
Water scarcity	(Frischknecht et al. 2008)
Land occupation - soil organic matter	(Milà i Canals et al. 2007)
Land occupation - biodiversity	Köllner, 2000 (Goedkoop and Spriensma 2000)
Land transformation - soil organic matter	(Milà i Canals et al. 2007)
Land transformation - biodiversity	Köllner, 2000 (Goedkoop and Spriensma 2000)

3.3.3 Environmental costs

The MMG method includes - besides the characterised scores per impact category - an aggregated single-score indicator, expressed in a monetary value (EURO). This aggregated score indicates the external environmental cost, i.e. the cost to avoid, reduce or compensate the damage caused by environmental impacts to a given level considered to be sustainable. The environmental cost is calculated by multiplying the characterised environmental impact indicators with their specific monetary value and adding these up to obtain the overall environmental cost (single score). The background for the determination of the monetary values is described in (De Nocker and Debacker 2015). In this research, the MMG monetary values of the central scenario for Western-Europe are selected for the E-LCA calculations (Table 3.4 and Table 3.5).

Table 3.4: Monetary values (central scenario) for the CEN indicators (De Nocker and Debacker 2015).

CEN indicators	Unit	Monetary value (€/unit)
Global warming	kg CO2 equiv.	0.1
Ozone depletion	kg CFC-11 equiv.	49.1
Acidification of soil and water	kg SO2 equiv.	0.43
Eutrophication	kg $(PO4)^{3-}$equiv.	20
Photochemical ozone creation	kg Ethene equiv.	0.48
Depletion of abiotic resources - elements	kg Sb equiv.	1.56
Depletion of abiotic resources - fossil fuels	MJ, net caloric value	0

Table 3.5: Monetary values (central scenario) for the CEN+ indicators (De Nocker and Debacker 2015).

CEN + indicators	Unit	Monetary value (€/unit)
Human toxicity - cancer effects	CTUh	665109
Human toxicity - non-cancer effects	CTUh	144081
Particulate matter	kg PM2,5 equiv.	34
Ionising radiation - human health	kg U235 equiv.	9.7E-04
Ionising radiation - ecosystems	CTUe (per kBq)	3.7E-05
Ecotoxicity - freshwater	CTUe	3.7E-05
Water scarcity	m^3 water equiv.	
Land occupation - soil organic matter	kg C deficit	2.7E-06
Land occupation - biodiversity		
Urban	m^2a	0.3
Agricultural	m^2a	6.0E-03
Forest	m^2a	2.2E-04
Land transformation - soil organic matter	kg C deficit	2.7E-06
Land transformation - biodiversity	m^2	Not available

Compared to other weighting methods, the advantage of expressing environmental impacts in monetary values is the possibility to internalize environmental externalities by calculating the sum of the financial and environmental costs, further referred to as total costs. In contradiction to the financial cost calculations, no discounting of future environmental costs is applied. A real growth rate and discount rate of 0% are used so that future environmental costs are equally valued as present environmental costs (Table 3.1)[5]. This approach is chosen in order to avoid burden shifting in time.

3.4 Assessment of the social performance

An assessment of the social performance was not included in the original SuFiQuaD method. Similar to the economic and environmental performance, a life cycle approach can be used to assess social impacts, following the principles of Social Life Cycle Assessment (S-LCA) (Benoît et al. 2009). However, as stated in a recent report of the Joint Research Center of the European Commission (Sala et al. 2015), the development of S-LCA is still in a preliminary stage and the reliability, robustness and applicability of current approaches should be improved. Moreover only a few applications in the building sector are known by the author (Chang et al. 2011; Hosseinijou et al. 2014).

Social aspects can also be evaluated based on a Multi-Criteria Analysis (MCA). An example is the approach proposed by the EN 16309 standards for the assessment of the social performance of buildings (CEN 2014). This approach consists of a combination of quantitative and qualitative indicators subdivided in 6 main categories[6]:

- Accessibility
- Adaptability
- Health and comfort
- Impacts on the neighbourhood[7]
- Maintenance and maintainability
- Safety and security

These categories cover a wide range of issues and are not limited to strictly social aspects as many indicators are related to functional and technical characteristics of the building. These indicators hence are a mixture of social performance indicators and building quality indicators.

[5] This assumption differs from the SuFiQuaD and MMG E-LCA method where a social discount rate of 1% is assumed.

[6] The categories "Sourcing of materials and services" and "Stakeholder involvement" are not yet ready for standardisation and therefore not included in the current standards.

[7] This category focuses on local impacts generated by the building, including noise, emissions to outdoor air, soil and water, glare/overshadowing and shocks/vibrations.

In this research, the MCA approach is selected for the assessment of the social performance, as S-LCA is not mature enough. To be in line with the global structure of the SuFiQuaD method, the social performance is evaluated as a part of the quality assessment, which is also based on MCA. However, a clear distinction is kept between the evaluation of socio-cultural qualities and other quality aspects in order to avoid an unclear mixture of both, such as in the EN 16309 standards. The assessment of socio-cultural qualities, together with other neighbourhood qualities is further elaborated in Chapter 5.

3.5 Quality assessment

In the SuFiQuaD method (Allacker 2010; Allacker et al. 2013a), building qualities are assessed based on a refinement of an existing method for the quality evaluation of housing in Belgium, entitled "Method for the evaluation of the quality of dwellings in the design phase" (Ministerie van de Vlaamse Gemeenschap -bestuur huisvesting 1991). Quality criteria are organized according to a hierarchical structure. In the refined method, this structure consists of four main aspects[8]: dimensional characteristics, functional characteristics, technical characteristics and the surroundings of the dwellings. The main aspects are subdivided in different sub-aspects, which in turn can be subdivided in sub-sub-aspects. At the different levels, weighting factors are assigned in order to calculate a global quality score for each dwelling. An overview of the main aspects and sub-aspects is given in Table 3.6.

While the dimensional, functional and technical characteristics mainly include building related quality criteria, the category "surroundings of the dwelling" focuses on the qualities of the location, both in the direct and broader environment. Aspects evaluated in this category are the provision of a healthy and safe environment, social contact, accessibility and the provision of services.

In this dissertation, a framework is developed to evaluate qualities at the neighbourhood level, based on a literature review of existing scoring tools for neighbourhoods (see Chapter 2). Besides the qualities already included in the SuFiQuaD method, additional quality aspects are considered related to the social performance (i.e. socio-cultural qualities), site and process qualities. The framework structure and quality aspects included are described in Chapter 5.

[8] The original method consisted of five main aspects. The last aspect, "Financial cost", is not included in the refined method as it is evaluated as part of the LCC approach.

Table 3.6: Main quality aspects and sub-aspects assessed in SuFiQuaD (Allacker 2010).

Main quality aspects	Sub-aspects	Weighting (%)
Dimensional characteristics		**38%**
	Size of rooms	15%
	Room width	10%
	Windows size and orientation	9%
	Efficient use of floor area	4%
Functional characteristics		**23%**
	Available length of furniture	7%
	Relation between the different rooms	11%
	Flexibility and adaptability	5%
Technical characteristics		**18%**
	Safety	1%
	Acoustical performance	5%
	Technical installations	10%
	Surface of materials: maintenance[9]	2%
Surroundings of the dwelling		**22%**
	Direct surroundings	12%
	Broader surroundings	10%

3.6 Life cycle stages and system boundaries

As mentioned in the previous paragraphs, the entire neighbourhood life cycle is evaluated within the life cycle approach. In accordance with the MMG method, a life span of 60 years is considered (Allacker et al. 2013b). Although the average life span of buildings in Belgium is usually longer than 60 years, it is assumed that after 60 years, most buildings undergo a thorough renovation leading to the demolition of many of the original materials (Allacker et al. 2013b).

An overview of the life cycle stages and system boundaries is provided in Figure 3.3. Compared to the original SuFiQuaD method the subdivision in life cycle stages was adapted to be in line with the European standards related to the sustainability of construction works (CEN 2010; CEN 2011; CEN 2015). In these standards, the life cycle of a building is divided into three main stages: the before use stage, use stage and End-Of-Life (EOL) stage. Those stages are further subdivided into modules with clearly defined boundaries. In this research, this modular structure was slightly adapted to include additional aspects such as the impact of user transport and primary land use. A brief description of the life cycle stages and modules is provided in the subsequent paragraphs. Adaptations and clarifications with respect to the European standards are systematically mentioned.

[9] This quality aspect focuses on the ease of cleaning of interior surfaces, which is not assessed as a cost factor in the LCC (Allacker 2010).

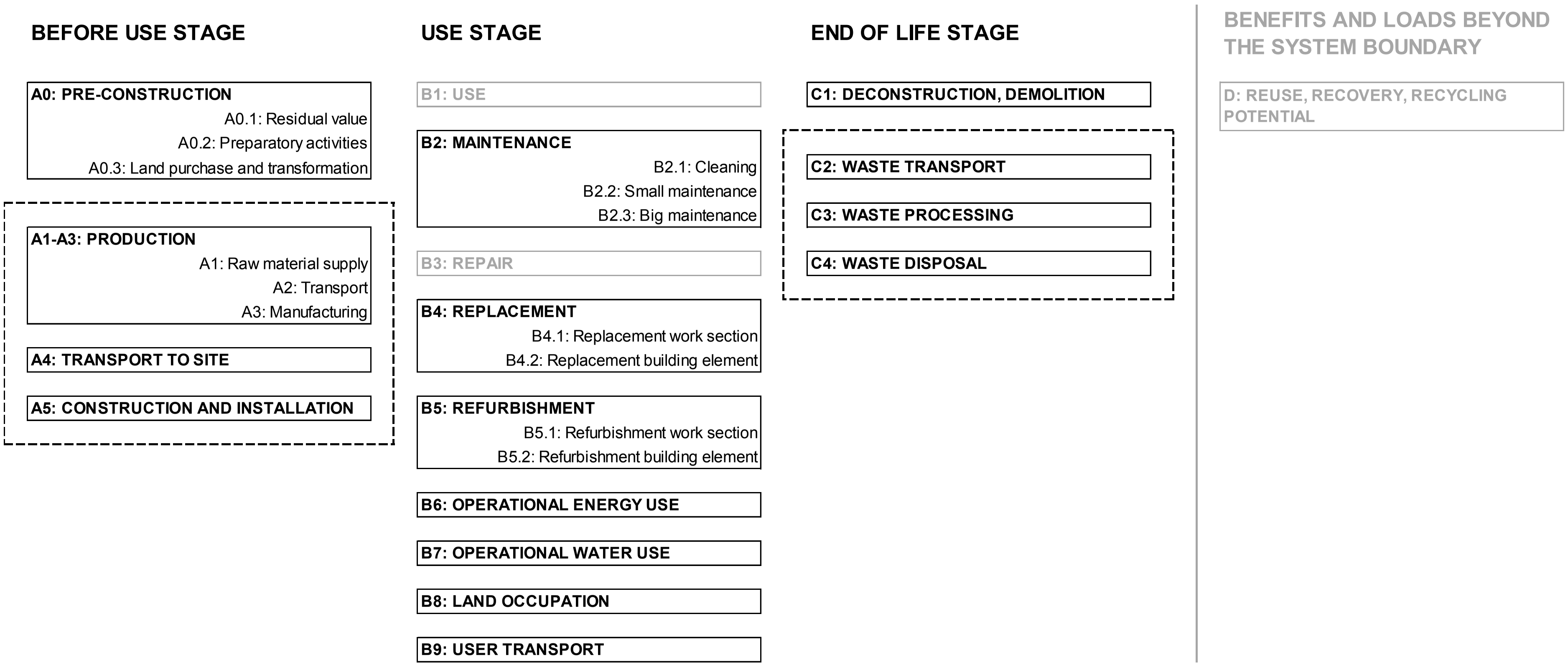

Figure 3.3: Life cycle stages and system boundaries, based on (CEN 2010; CEN 2011; CEN 2015). Modules indicated in grey are not included in the assessment. Modules surrounded with dotted lines are aggregated for the LCC calculations.

3.6.1 Before use stage

The before use stage includes all processes prior to the use of the neighbourhood, i.e. pre-construction (as defined below), product manufacturing, transport to site and construction. The structure of the before use stage differs between the LCC and E-LCA calculations. For the LCC calculations, the product manufacturing, transport to site and construction are not reported separately as cost data are only available in aggregated form, i.e. end prices of construction products (including material, labour and indirect costs). The designer's cost, i.e. professional fees for urban planners, architects and engineers are not included in the calculations.

A0: Pre-construction

According to the European standards EN 16627 (CEN 2015), module A0 includes the activities carried out before the start of the construction works such as the purchase of a site or impacts related to the demolition of an existing building. In this research, this module is also used to report the financial and environmental impact related to existing building components in the context of a refurbishment [10]. Module A0 is subdivided into three submodules: "A0.1: Residual value", "A0.2: Preparatory activities" and "A0.3: Land purchase and transformation".

First, "A0.1: Residual value" refers to the impact of existing building components, which is partially allocated to the new life cycle of the renovated building or neighbourhood. For all existing building components, which have not reached the end of their service life at the time of the refurbishment, a residual value or impact is calculated. The residual impact is calculated as linearly proportional to the ratio of the remaining life span of the building components to their predicted service life, based on Formula [3.5] (Figure 3.4):

$$RI_t = I_s \frac{(y_e - y_t)}{(y_e - y_s)} \qquad [3.5]$$

With:

- RI_t = residual impact of the building component at the year of intervention (year t)
- I_s = impact of the building component at the year of construction
- y_e= predicted year of demolition of the building component, based on service life
- y_t = year of intervention
- y_s = year of construction of the building component

Second, "A0.2: Preparatory activities" covers all preparatory activities required for the refurbishment. More specifically, this submodule includes the demolition of existing building components and the related waste transport, processing and disposal.

[10] Although the focus of this research is on newly built neighbourhoods, the first steps to assess the impact of refurbishment projects are already elaborated.

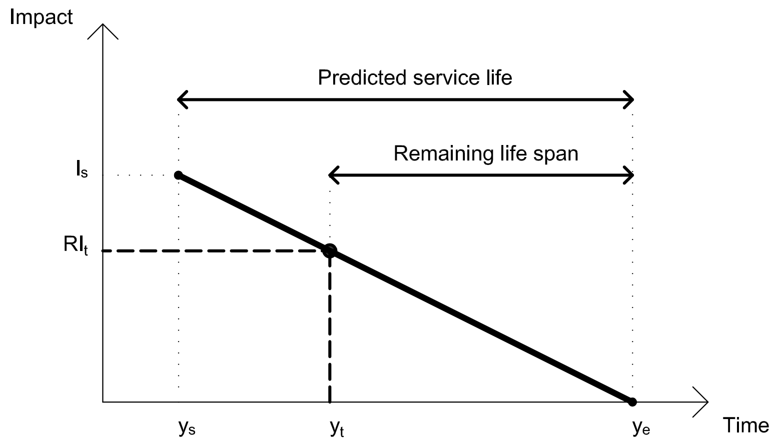

Figure 3.4: Calculation of the residual impact (RI_t) of a building component at year t (y_t). The initial impact (I_s) is amortized over a predicted service life of (y_e-y_s).

Third, “A0.3: Land purchase and transformation” includes the initial impacts related to the neighbourhood primary land use[11]. For the E-LCA calculations, this module focuses on the environmental impact resulting from a transformation in land use type, such as for example from forest to urban land use. Concerning the LCC calculations, it includes the financial cost of land purchase, including all taxes. The assessment of the impact of primary land use in neighbourhoods is further elaborated in Chapter 5.

A1-A3: Production

“A1-A3: Production” covers the impact related to the production of building materials. In accordance with the European standards (CEN 2011), the following processes are included: extraction of raw materials (module A1), transport of raw materials to the manufacturer (module A2) and manufacturing (module A3). As the LCI database used for the environmental impact calculations (i.e. Ecoinvent version 2.2) does not follow this modular subdivision, the data are reported in aggregated form for the whole product stage (modules A1 to A3).

A4: Transport to site

This module covers the transportation of building materials and products from the factory to the construction site. Concerning the E-LCA calculations, the impact of transport is assessed based on transportation scenarios for the Belgian context, defined per material category. An overview of the transportation scenarios is given in (Allacker et al. 2013b). In contrast to the European standards, the transportation of construction equipment, such as cranes, is not taken into account in the E-LCA calculations, due to lack of data (Allacker et al. 2013b).

[11] Neighbourhoods are responsible for two types of land use interventions: primary land use, i.e. the neighbourhood spatial footprint and secondary land use, associated with the resource extraction, production, transport and end-of-life treatment of construction products (Allacker, Souza, & Sala, 2014) and the operational energy use, operational water use and user transport. This is further elaborated in Chapter 5.

Furthermore the environmental impact of material losses during transport is allocated to module “A5: Construction and installation” via a global add-on for all material losses during transportation and construction, as no detailed information is available.

A5: Construction and installation

Construction activities and material losses on the construction site are included in Module A5. Construction activities cover the impact of construction equipment and energy use for machinery. Concerning the construction of buildings, only the environmental impact of excavation works is considered in the E-LCA calculations[12], due to a lack of environmental data on other construction activities. As most of the construction works are still manual labour and not automated, it is however expected that the impact of these activities is negligible. Concerning the construction of road infrastructure and open spaces, the environmental impact of construction equipment, such as asphalt and concrete paving machines, is assessed based on inventory data reported in (Gschösser 2011).

The environmental impact of material losses, due to surpluses, trimmings or breakage is calculated based on a global add-on of 5% on all material quantities (Allacker et al. 2013b). For those materials, the environmental impact is calculated as the sum of the impact of material production, transportation and waste management.

3.6.2 Use stage

The use stage covers all the processes between the completion of the construction works and the demolition of the neighbourhood at the end of the life cycle. Included processes are maintenance activities (including cleaning), replacement and refurbishments, and operational energy and water use. Compared to the European standards, two additional modules, are added to assess the impact of land occupation and user transport (modules B8 and B9).

B1: Use

Module B1 includes the impact arising from the normal conditions of use of the neighbourhood. Regarding the financial impact, it covers costs such as taxes, regulatory, insurance and security costs (CEN 2015). As these costs highly depend on policies and/or are quite difficult to predict, they are not included in the assessment.

Concerning the environmental impact, this module should be used to assess the impact of the release of substances from building materials in the local environment (CEN 2011). As the inclusion of local impacts in building E-LCA is still under development (Allacker 2010) and no further research is known by the author, it is not included in this dissertation.

[12] The impact of blowing of insulation materials on the construction site is for practical reason included in module A1-A3 (Production).

B2: Maintenance

In this research, module B2 is further divided into three submodules differentiating between the impact of cleaning, small maintenance and big maintenance activities. To assess the impact of these interventions, a number of scenarios have been defined related to the type and frequency of each maintenance process. More information about the scenarios related to the maintenance of the building elements can be found in (Allacker 2010; Allacker et al. 2013a; Allacker et al. 2013b). The scenarios used for the road infrastructure and open spaces are elaborated in more detail in Chapter 7.

B3: Repair

According to the CEN standards (CEN 2011), repair is defined as the renewal, replacement or mending of worn, damaged or degraded building parts. An example is the replacement of a broken window pane. In the MMG E-LCA method, planned maintenance activities and replacements are assessed in module B2 and B4 respectively. Replacements due to accidental damage or failure are not considered as they are difficult to predict. Module B3 is hence not included in the assessment (Allacker et al. 2013b).

B4: Replacement

The impact of the replacement of worn building components is included in module B4. It covers the impact of the demolition, waste transport and waste management of the removed components and the production, transportation and construction of the new components. Module B4 is divided into two submodules. The first submodule refers to the replacement of work sections, such as the replacement of gypsum plaster on brickwork every 40 year. The second submodule refers to the whole replacement of building elements, such as the replacement of non-load-bearing internal walls (including all finishes) every 30 year.

More information about the replacement scenarios for the work sections and building elements can be found in (Allacker 2010; Allacker et al. 2013a; Allacker et al. 2013b). The replacement scenarios used for the road infrastructure and open spaces are further elaborated in Chapter 7.

B5: Refurbishment

Module B5 covers the impact of future refurbishments. Similar to module B4, a distinction is made between interventions on the level of work sections and on the level of building elements (submodule B5.1 and B5.2). An example of a refurbishment at the level of work sections is a facade upgrade resulting in the replacement of the insulation layer and external finishes of the external walls. An example of a refurbishment at the level of building elements is a change of the internal building layout requiring the demolition of a number of internal walls. Although the assessment of future refurbishments was developed conceptually in this dissertation, no future refurbishments are included in the assessment of the schematic neighbourhood models (see Chapter 8).

B6: Operational energy use

This module includes the impact of energy use for heating , production of domestic hot water, ventilation, lighting and appliances in buildings. Cooling is not considered as it should be avoided in residential buildings in the Belgian moderate climate (Allacker 2010). Besides the energy use in buildings, the energy use for road lighting is also assessed in this module. The assessment of operational energy use in neighbourhoods is further elaborated in Chapter 5.

B7: Operational water use

Module B7 covers the impact of tap water consumption and treatment of waste water during the operation of the neighbourhood. Regarding tap water, only the private tap water consumption (in buildings and for gardens) is considered. The tap water consumption for the cleaning and irrigation of infrastructure and public open spaces is not included due to a lack of available data. The assessment of the operational water use in neighbourhoods is further elaborated in Chapter 5.

B8: Land occupation

Besides initial impacts related to land purchase and land transformation (module A0), the neighbourhood spatial footprint (primary land use) is responsible for a land occupation impact during the neighbourhood life span. This impact is assessed in module B8. The method used for the environmental impact assessment is described in Chapter 5.

Concerning the LCC calculations, land occupation taxes are not considered due to a lack of statistical data on the cadastral income, which is used for the calculation of taxes on immovable property[13].

B9: User transport

Module B9 focuses on the impact of the transportation of the inhabitants, which is influenced by the neighbourhood location and the availability of transport amenities. The calculation of the impact of user transport is further elaborated in Chapter 5.

3.6.3 End-of-life stage

The end-of-life stage covers the impact of the neighbourhood demolition and the related waste transport, processing and disposal. At the end of life of the neighbourhood[14] no residual value is considered for the building components that have not yet reached the end of their service life as it is assumed that the whole neighbourhood is being demolished.

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[13] In Belgium taxes on immovable property are calculated based on the cadastral income for the reference year 1975 (Flemish Government 2017). Statistical data on the cadastral income depending on the location and type of property are not available.

[14] In practice, neighbourhoods are often demolished in different stages. However, in this research, a single year is assumed for the EOL of the neighbourhood.

For the LCC calculations the impact of waste transport, processing and disposal is not reported separately as cost data are only available in aggregated form, i.e. global prices for waste removal (Allacker 2010).

C1: Deconstruction, demolition

Module C1 includes the impact of the deconstruction and demolition of the neighbourhood. Concerning the E-LCA calculations, the same demolition process is assumed for all materials, due to a lack of more detailed LCI data (Allacker et al. 2013b).

C2: Waste transport

This module covers the transportation of demolition waste from the demolition site to the disposal or to the place where the end-of-waste state is reached (for the materials that are intended for reuse, recycling or energy recovery). By convention, the end-of-waste state is reached at the exit gate of the sorting facility or collection point as it corresponds to the point where the materials are no longer considered as waste but as secondary raw materials (Allacker et al. 2013b). Concerning the E-LCA calculations, the environmental impact of waste transport is calculated based on transportation scenarios for the Belgian context, defined per waste category. An overview of the transportation scenarios is given in (Allacker et al. 2013b).

C3: Waste processing

Module C3 focuses on the waste processing of materials that are intended for reuse, recycling or energy recovery[15]. Only the processes before the end-of-waste state is reached are included. This encompasses the impact of sorting in a sorting facility but also the crushing of inert materials. The scenarios for the modelling of sorting and crushing processes are described in (Allacker et al. 2013b).

C4: Waste disposal

For the waste fractions that are intended for incineration (without energy recovery) or for landfill, the impact of waste disposal, including all the previous sorting processes, is assessed in module C4. In order to calculate the environmental impact of waste disposal, waste scenarios for the Belgian context have been defined for various waste categories. These scenarios are described in (Allacker et al. 2013b).

3.6.4 Benefits and loads beyond the system boundary

Benefits and loads related to the further reuse, energy recovery and recycling after the EOL stage may be assessed in module "D: Reuse, recovery, recycling potential". In accordance with the MMG E-LCA method module D is not included in this research as it falls outside the system boundaries and is not compulsory (CEN 2010). However module D is intended to be

[15] The waste incineration should fulfil with an energy recovery efficiency rate of minimum 60% to be considered as energy recovery.

mandatory in the future update of the CEN standards in order to better capture the benefits related to circular economy and the increased reuse and recycling of building materials.

3.7 Conclusions

This chapter presented the integrated life cycle approach for neighbourhoods. The proposed approach fulfils with a number of recommendations formulated in the previous chapter. First, it covers a wide range of sustainability issues by combining an assessment of the economic, environmental and social performance with an assessment of the neighbourhood qualities. Second, the approach is mainly based on life cycle methodologies, considering the neighbourhood impacts over the entire neighbourhood life cycle. Except for the assessment of the social performance and the quality assessment which are based on MCA, the economic and environmental performance are evaluated based on respectively LCC and E-LCA. Third, the method builds upon the existing SuFiQuaD method for the assessment of buildings. By using the same methodological approach, the life cycle results at the building level can be upscaled to the neighbourhood level. The methodology for upscaling the building assessment to neighbourhoods is presented in Chapter 4. Finally, the approach is characterized by its modularity and possibilities for future extensions. Even if the focus of this research is on newly built residential neighbourhoods, the approach allows for an assessment of refurbishment projects and non-residential buildings.

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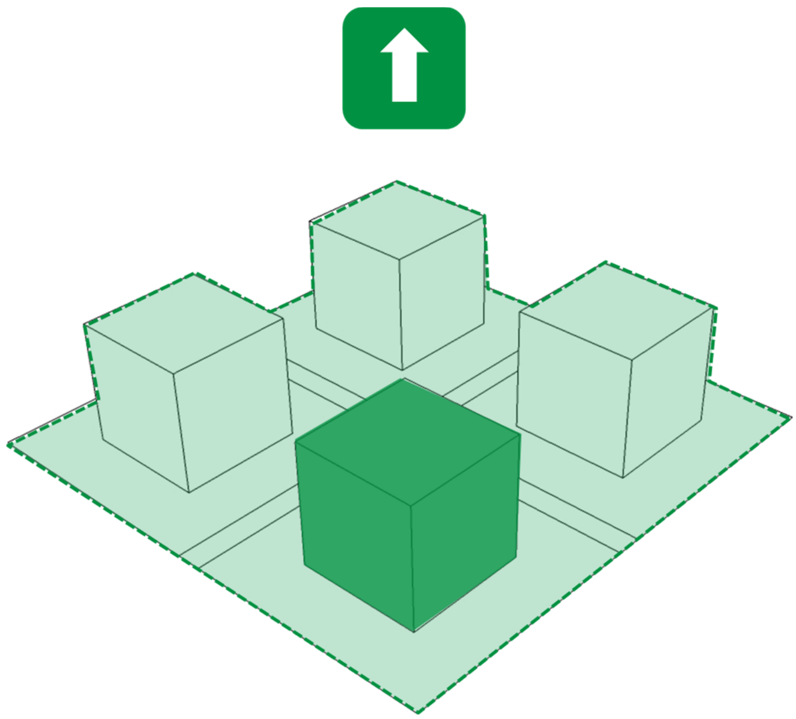
CHAPTER 4

Extension to the neighbourhood scale level

This chapter focuses on the methodology to upscale the integrated life cycle approach from the building to the neighbourhood scale level. The neighbourhood scale level is defined and a number of indicators of urban density are described. A hierarchical assessment structure based on the element method for cost control is presented.

The approach for extending the element method from the building to the neighbourhood scale level is published in several papers focussing on the financial and/or environmental impact of road infrastructure and neighbourhoods (Trigaux et al. 2014; Trigaux et al. 2016; Trigaux et al. 2017).



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4.1 Neighbourhood scale level

4.1.1 A bottom-up approach to define neighbourhoods

The literature review of existing tools (Chapter 2) revealed that there is no clear definition of the neighbourhood scale level. The objects analysed vary from small scale to large scale developments. In (Berghauser Pont and Haupt 2010), a bottom-up approach is followed to define different levels of aggregations from the building to the district scale. This bottom-up approach is particularly appropriate for this research as the main objective is to upscale the sustainability assessment from the building to the neighbourhood scale. Starting from the building level, Berghauser Pont & Haupt distinguish between the level of a lot, an island, a fabric and a district (Figure 4.1):

- A lot, parcel or plot includes the built and non-built areas designated for a building. The borders of a lot correspond to the legal boundaries defined in the cadastre.
- An island consists of the combination of a number of lots. The borders of an island are defined by the surrounding streets. An example of an island is the urban block found in traditional cities.
- A fabric is defined as a collection of similar islands, including the network of streets.
- A district or neighbourhood consists of a collection of fabrics, together with non-built areas, such as additional street network and open spaces.

Based on this approach, a number of schematic residential neighbourhood models with diverse built densities are defined to be used as case studies. The definition of the neighbourhood models is further elaborated in Chapter 8.

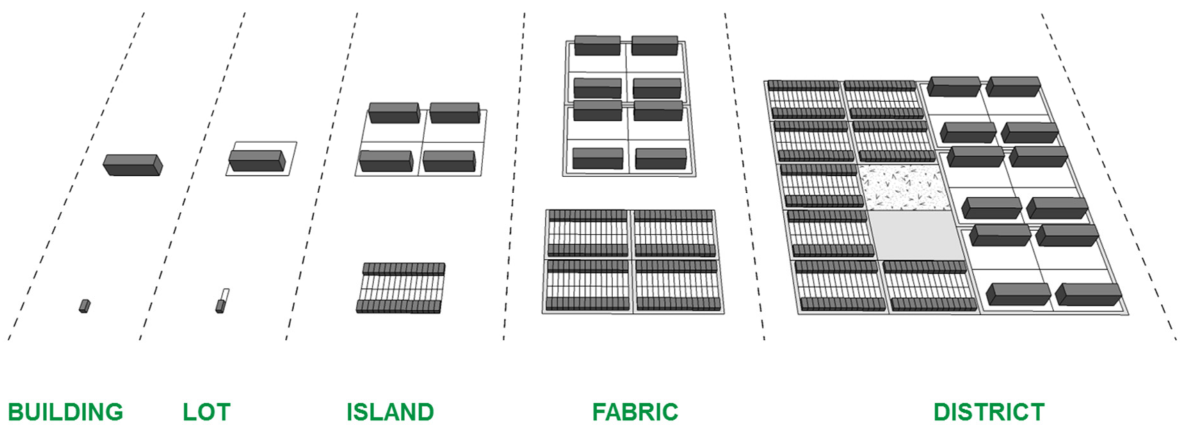

Figure 4.1: Aggregation levels from the building to the district scale, based on (Berghauser Pont and Haupt 2010).

4.1.2 Indicators of urban density

In this PhD dissertation the influence of the built density on the environmental and financial impact of neighbourhoods is investigated (see Chapter 8). It is hence important to define indicators that characterise the density of a neighbourhood. In literature various urban density indicators are available (Berghauser Pont and Haupt 2010). In this research, the three basic indicators proposed by (Berghauser Pont and Haupt 2010) are selected[1]: Floor Space Index (*FSI*), Ground Space Index (*GSI*) and Network density (*N*). These indicators may be used at the different levels of aggregations (see Section 4.1.1) and are calculated based on four variables (Figure 4.2):

- Base land area (*A*): land area of the urban fragment;
- Network length (*L*): length of the circulation network. A distinction is made between the internal network, i.e. the network inside the base land area (indicated by continuous lines in Figure 4.2) and the external network, i.e. the network at the border of the base land area (indicated by dotted lines in Figure 4.2). Only half of the external network is allocated to the analysed urban fragment as the other half belongs to the surrounding fragments;
- Gross floor area (*F*): sum of all floor areas, measured for each storey;
- Built up area or footprint (*B*): floor area, measured at ground level.

The Floor Space Index (*FSI*) refers to the building intensity and is calculated as the ratio of the gross floor area to the base land area, using Formula [4.1] (Berghauser Pont and Haupt 2010):

$$FSI = \frac{F}{A} \tag{4.1}$$

With:

- F = gross floor area (m²)
- A = base land area (m²)

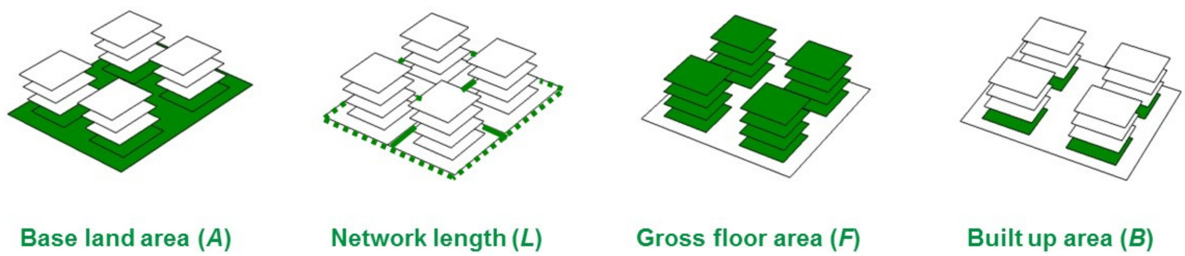

Figure 4.2: Schematic representation of four variables used for the calculation of urban density indicators, based on (Berghauser Pont and Haupt 2010).

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[1] The selected indicators are key figures of the built density. They do not aim to assess the desirability of the built density and its influence on the neighbourhood qualities.

The Ground Space Index (*GSI*) characterizes the building coverage and is calculated as the ratio of the built-up area to the base land area, using Formula [4.2] (Berghauser Pont and Haupt 2010):

$$GSI = \frac{B}{A} \qquad [4.2]$$

With:

- B = built up area (m²)
- A = base land area (m²)

The Network density (*N*) characterizes the concentration of networks in an area and is calculated as the ratio of the network length to the base land area, using Formula [4.3](Berghauser Pont and Haupt 2010):

$$N = \frac{L}{A} = \frac{\left(\sum L_i + \frac{\sum L_e}{2} \right)}{A} \qquad [4.3]$$

With:

- L_i = length of internal network (m)
- L_e = length of external network (m)
- A = base land area (m²)

In addition to these three indicators, a fourth indicator is defined in this research to characterize the network intensity per gross floor area. This additional indicator, which is further referred to as Network Floor Index (NFI), is calculated using Formula [4.4]:

$$NFI = \frac{L}{F} = \frac{\left(\sum L_i + \frac{\sum L_e}{2} \right)}{F} \qquad [4.4]$$

4.2 Element method for cost control

4.2.1 Hierarchical subdivision and scale levels

Due to the complexity of neighbourhoods a well-structured evaluation is required to deal with the huge amount of data. In the SuFiQuaD method the assessment structure is based on the element method for cost control (Allacker 2010). The basic principle is the hierarchical subdivision of the building into building elements, such as external walls, roofs and technical services. These building elements can then again be subdivided in several work sections which are composed of one or more building materials (Figure 4.3).

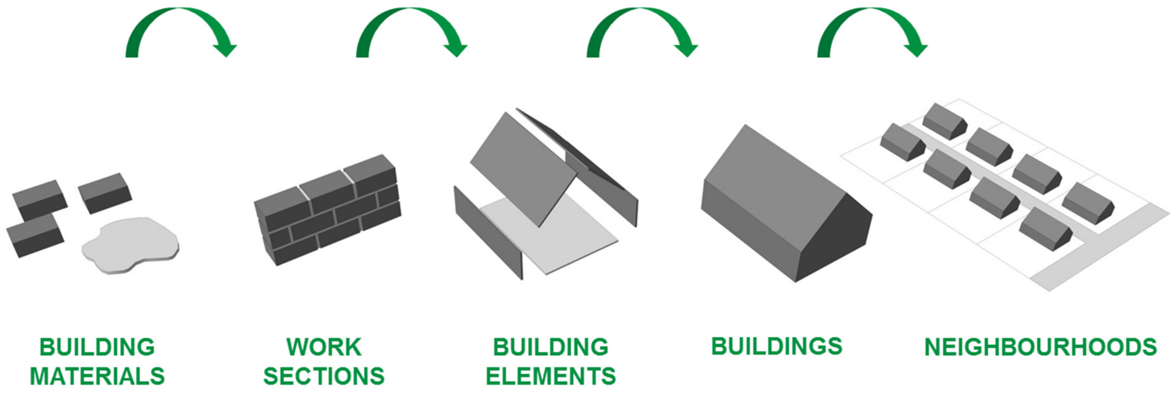

Figure 4.3: Element method for cost control and scale levels (Trigaux et al. 2014).

In consequence, an analysis can be made at various scale levels, each higher level building on the lower levels. The following levels are considered: building materials (e.g. brick, mortar, plaster), work sections (e.g. brickwork, plasterwork), building elements (e.g. external wall including finishes) and buildings. In this research, the element method is extended to evaluate neighbourhoods. In accordance with the bottom-up approach presented in (Berghauser Pont and Haupt 2010), neighbourhoods are defined as a combination of (residential) buildings, networks (e.g. roads, utilities) and open spaces (e.g. squares, parks) (Figure 4.3).

The hierarchical structure of the element method allows using the results from the lower scale levels for analysis at the higher scale levels. It is therefore particularly adapted for upscaling the life cycle approach from the building to the neighbourhood scale level. Furthermore, it can be used during the different stages of the design process. In the sketch design, the designer can make rough impact estimations by using a number of predefined building elements. This is very useful in the context of a screening LCA study, such as recommended by the EeBGuide (European Commission 2017). During the design process the rough impact estimations can then gradually be refined when the exact composition of the elements is known. These rough estimations are especially useful in the master planning stage as the focus of the urban designer is on the urban layout and geometry rather than on the choice of materials and technical solutions.

4.2.2 BB/SfB-plus classification

Elements, macro-elements and sub-elements

The implementation of the element method in SuFiQuaD is based on the BB/SfB-plus classification (De Troyer 2008), which is an extension of the Belgian version of the international CI/SfB classification system (Ray-Jones and Clegg 1978; De Troyer et al. 1990). In this classification system, elements are subdivided in nine main categories, according to their function (Table 4.1).

Table 4.1: Main element categories BB/SfB (De Troyer 2008).

Code	**Name element category**
(1-)	Ground, substructure
(2-)	Structure, primary elements, carcass
(3-)	Secondary elements, completion of structure
(4-)	Finishes to structure
(5-)	Services, mainly piped, ducted
(6-)	Services, mainly electrical
(7-)	Fittings
(8-)	Loose furniture equipment
(9-)	External elements, other elements

In each category functional elements are defined by a two digit code, put between brackets “(xx)”. Examples of functional elements included in the category “(2-) Structure, primary elements, carcass” are:

- (21) primary elements of external walls
- (22) primary elements of internal walls
- (23) primary elements of floors
- (27) primary elements of roofs

The functional elements can be further specified by using a decimal code“(xx.x)”. For example, “(21) primary elements of external walls” can be subdivided in:

- (21.1) primary elements of load-bearing external walls
- (21.3) primary elements of non-load-bearing external walls
- (21.4) primary elements of curtain walls

Compared to the original CI/SfB classification, the BB/SfB-plus classification system introduces two additional concepts: macro-elements and sub-elements (De Troyer 2008) (Figure 4.4).

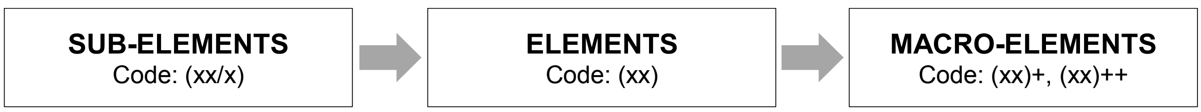

Figure 4.4: Structure of the BB/SfB-plus classification, including sub-elements, elements and macro-elements.

First, macro-elements are space delimiting building elements[2], such as external walls, internal walls, floors and roofs, which are composed of different functional elements. Macro-elements are described based on the following codes: "(xx)+" which refers to the primary element, together with the finishes and "(xx)++" which refers to the primary element, together with the finishes and openings. As an example, the following macro-elements can be defined based on the functional element "(21) primary elements of external walls":

- (21)+ = primary element of external wall (21), external finishes (41) and internal finishes (42)
- (21)++ = primary element of external wall (21), external finishes (41), internal finishes (42) and openings (31)

Second, sub-elements are a further subdivision of elements based on a functional criterion. Sub-elements are described by using a slash after the element code "(xx/x)". As an example, the following sub-elements can be defined based on the functional element "(21) primary elements of external walls":

- (21/1) = infrastructure for external wall
- (21/2) = primary part of external wall
- (21/4) = treatment of external wall

External elements (9-)

In order to model neighbourhoods, constructions outside the building such as road infrastructure, open spaces and utilities should be integrated in the existing building assessment. The element category "(9-) External elements, other elements" can be used for this purpose. An overview of the functional elements for this category is given in Table 4.2.

As an example, works related to road infrastructure, squares and green areas can be defined based on the functional element "(94) Ground surface treatments". This functional element can be further specified by using a decimal code to make a distinction between hard surfaces, soft/planted surfaces and water surfaces (Table 4.3). In accordance with the BB/SfB-plus principles, element (94) can be subdivided in sub-elements, covering the different road work sections such as road base, road surfacing and road paint (Table 4.4).

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[2] The BB/SfB-plus classification makes a distinction between space delimiting elements and space servicing elements, such as piped and electrical services. The concept of "macro-elements" is only applicable to space delimiting elements.

Table 4.2: BB/SfB-plus classification for external elements (9-) (De Troyer 2008).

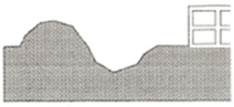
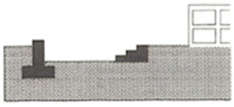
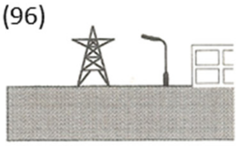
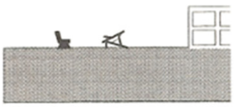
Code and pictogram	Name element	Examples
(91) 	Ground preparation	Ground clearing, shaping
(92) 	Minor structure	Shelters, sheds, retaining walls
(93) 	Enclosures	Fences, gates
(94) 	Ground surface treatments	Roads, squares, green areas
(95) 	Piped services	Sewer, district heating ductwork
(96) 	Electrical services	Outdoor lighting
(97) 	Fittings	Hoardings, outdoor benches

Table 4.3: Further specification for the functional element "(94) Ground surface treatments", based on CI/SfB (Ray-Jones and Clegg 1978).

Code	Name element	Examples
(94.1)	Ground surface treatments – hard surfaces	Roads, paths, parking facilities, squares
(94.2)	Ground surface treatments – soft, planted surfaces	Parks, gardens
(94.3)	Ground surface treatments – water surfaces, pools	Pools, fountains
(94.8)	Ground surface treatments – other types	-

Table 4.4: Proposed subdivisions in sub-elements for the functional element “(94) Ground surface treatments”, in line with BB/SfB-plus (Trigaux et al. 2014).

Code	Name sub-element	Examples
(94/0)	Ground surface treatments - excavation	Excavation for roads
(94/1)	Ground surface treatments - base	Road base, road sub-base
(94/2)	Ground surface treatments - surfacing	Road surface, binder
(94/4)	Ground surface treatments - finishing	Road paint
(94/5)	Ground surface treatments - piped services	Road drainage
(94/6)	Ground surface treatments - electrical services	Road lighting
(94/8)	Ground surface treatments - higher not included elements	Geotextile

4.2.3 Functional unit

Depending on the scale level analysed, different functional units are used. This dissertation includes two types of analyses. First, an analysis is carried out at the element level, consisting of the assessment of networks and open spaces (see Chapter 7). Networks such as roads, bicycle paths, footpaths and utilities are linear elements and the impacts are expressed per metre of element for a variant with a given width. Open spaces such as squares and green areas are planar elements and the impacts are expressed per m² of element.

Second, an analysis is carried out at the neighbourhood level, consisting of the assessment of a number of schematic residential neighbourhood models (see Chapter 8). Depending on the focus of the analysis, the impact may be expressed per m² of useful floor area (UFA)[3] or per inhabitant. An analysis per m² of (useful) floor area allows to compare different neighbourhood layouts and typologies. This approach is used in the element method and is also common in environmental impact assessment (Allacker 2010). However, it is not adapted for comparing housing typologies with a varying amount of floor area per person, as the preference would go to larger dwellings which often have a lower impact per m² of floor area, although the absolute impact is higher (Allacker 2010). In that case an analysis per inhabitant should be preferred. In this research, a fixed amount of floor area per person is assumed for the definition of the schematic neighbourhood models as the focus is to analyse the influence of the neighbourhood layout and density. Therefore the results are systematically expressed per m² UFA.

[3] In this research the useful floor area of a building is defined as the total floor area, excluding the area of circulation spaces shared by different housing units, such as collective stairs, corridors and elevators in apartment buildings.

4.3 Conclusions

This chapter describes the approach to extend the life cycle methodology from the building to the neighbourhood scale level. The proposed approach is based on the principles of the element method for cost control. A distinction is made between different scale levels (i.e. from building materials, work sections, building elements, buildings to neighbourhoods), where the results from the lower scale levels can be used for analysis at the higher scale levels.

This hierarchic structure allows to deal with the complexity of the neighbourhood system and the huge amount of data required in LCC and E-LCA. Furthermore, the approach is also appropriate for the first design stages as rough impact estimations can be made by using predefined building elements. This is very important at the neighbourhood scale level as the focus of the urban designer is on the urban layout and geometry rather than on the choice of materials and technical solutions.

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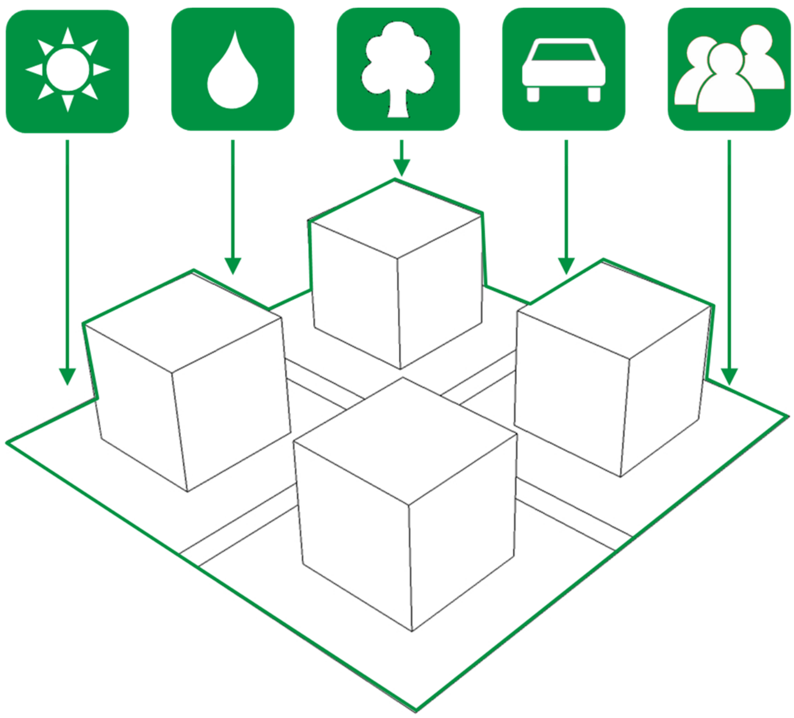
CHAPTER 5

Extension of the evaluation scope

This chapter focuses on the extension of the evaluation scope of the original SuFiQuaD sustainability assessment method by including additional aspects which are influenced by decisions taken at the neighbourhood scale. Five main aspects are described in detail, i.e. the assessment of operational energy use, operational water use, primary land use, user transport and neighbourhood qualities. Special attention is given to assessment methods which require limited input and are suited for the master planning phase of neighbourhoods.

The assessment methods described in this chapter are partly published in conference or journal papers (Trigaux et al. 2014; Trigaux et al. 2015; Trigaux et al. 2017a; Trigaux et al. 2017b).



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5.1 Operational energy use

This section describes the assessment of the impact of operational energy use in neighbourhoods. The operational energy use includes the energy use for spatial heating, domestic hot water, ventilation, lighting and appliances. Cooling is not considered as it should be avoided in residential buildings in the moderate Belgian climate (Allacker 2010)[1].

5.1.1 Energy use for heating

The energy use for heating in buildings can be considerably affected by urban planning decisions related to the neighbourhood layout, building geometry and shading interactions between buildings. Some studies focussing on the urban morphology and its impact on building compactness, access to sunlight, daylight and natural ventilation suggest that optimizing the urban morphology can lead to a reduction in energy use by a factor two (Ratti et al. 2005) (Salat 2009). However, the impact of urban planning decisions on energy consumption is often neglected because appropriate energy simulation tools are lacking (Ratti et al. 2005). The available tools are often too complex and require a large amount of input data, which are lacking in the urban planning phase.

To overcome this issue, a simplified approach is proposed to estimate the heating energy demand during the master planning phase of neighbourhoods. This approach consists of a design tool to optimise solar radiation and heating energy use in neighbourhoods, requiring limited input. The approach is described in two conference papers (Trigaux et al. 2014; Trigaux et al. 2015) and in an international journal article (Trigaux et al. 2017b).

Existing simulation tools

Various tools and methods are available to estimate solar gains and their impact on the heating energy use in buildings. In the Flemish Energy Performance of Buildings (EPB) regulation (Flemish Government 2017a), the impact of shading patterns, resulting from neighbouring buildings, trees, sheds or side walls, is simplified by defining a set of obstruction and overhang angles per window. For each window those angles are then projected on the visible part of the sky dome to calculate the reduction in direct and diffuse solar radiation, compared to unshaded conditions (Figure 5.1). The EPB method lacks the accuracy, however, to analyse the influence of the urban geometry and shading caused by neighbouring buildings (Trigaux et al. 2014). As illustrated in Figure 5.1 for a dwelling in a rectangular urban block, the EPB approximation can lead to an overestimation of shading patterns and hence to an underestimation of solar gains (Trigaux et al. 2014).

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[1] Overheating may be an issue in well-insulated residential buildings if shading is not addressed properly. However, overheating and cooling can only be assessed via dynamic simulations considering the thermal comfort hour by hour. As dynamic simulation tools are too input intensive and time consuming to be used in the master planning phase, these aspects are not included in this research.

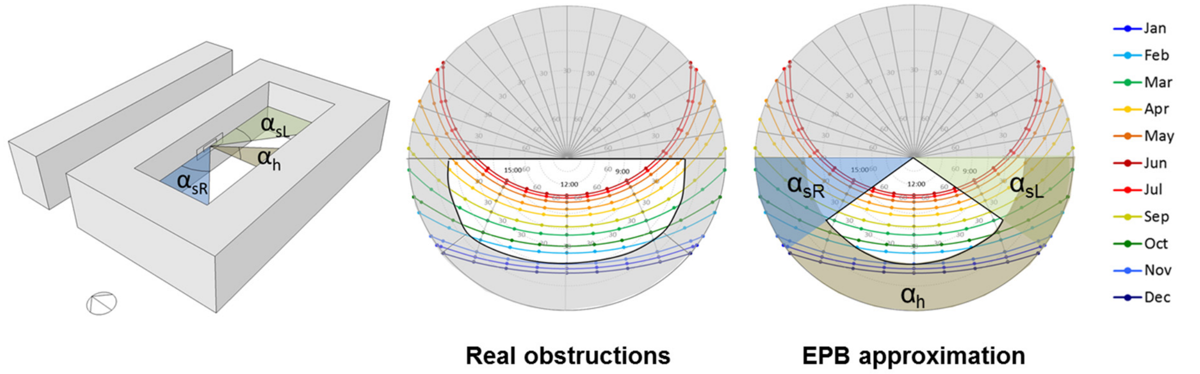

Figure 5.1: Stereographic projection of solar obstructions for a window in a rectangular urban block (solar trajectories for Belgium: 51°N). Real obstructions (left) are compared with the EPB approximation (right) (Trigaux et al. 2014).

Besides the simplified EPB method, tools exist which consider real obstructions, such as the energy simulation software EnergyPlus (U.S Department of Energy 2017). Those tools, however, are very complex and require a large amount of input data, which are most often not available in the urban planning phase.

With the development of Building Information Modelling (BIM), the use of 3D environments to retrieve input data for energy calculations is increasing. An example is OpenStudio, linking an enriched 3D Sketchup model with EnergyPlus (Trimble Inc. 2017; U.S. Department of Energy 2017; U.S Department of Energy 2017). This approach is used by several researchers. In (Ratti et al. 2005), data related to the urban geometry are extracted from digital elevation models of cities and used as input for energy calculations. In (Weytjens 2013) a plugin is developed to link a 3D SketchUp building model with an energy analysis based on the Flemish EPB regulation. The latter is particularly adapted to the early design stage, but the calculation of solar gains is simplified by using a fixed reduction factor for shading obstructions[2]. In the design tool developed in this research, the extraction of detailed data on solar obstructions from a SketchUp neighbourhood model is further investigated.

Structure of the design tool

The structure of the proposed design tool is illustrated in Figure 5.2. Based on a SketchUp 3D neighbourhood model, detailed information on solar obstructions is extracted by means of a plugin[3]. This information can then be visualised on sun-path diagrams and linked to solar gain calculations. In this research, solar gains are calculated based on a refinement of the existing Flemish EPB method, further referred to as EPB+ method. Finally, the data regarding solar gains are used as input for the calculation of the heating energy demand, based on the dynamic Equivalent Heating Degree Day (dEHDD) method (Trigaux et al. 2014). The solar gains and heating energy demand calculations are described in the subsequent paragraphs.

[2] The use of a fixed reduction factor for shading obstructions (with value of 0.6) is not accepted anymore in the most recent version of the EPB regulation (Flemish Government 2017a).

[3] The plugin is developed in collaboration with Bernard Oosterbosch.

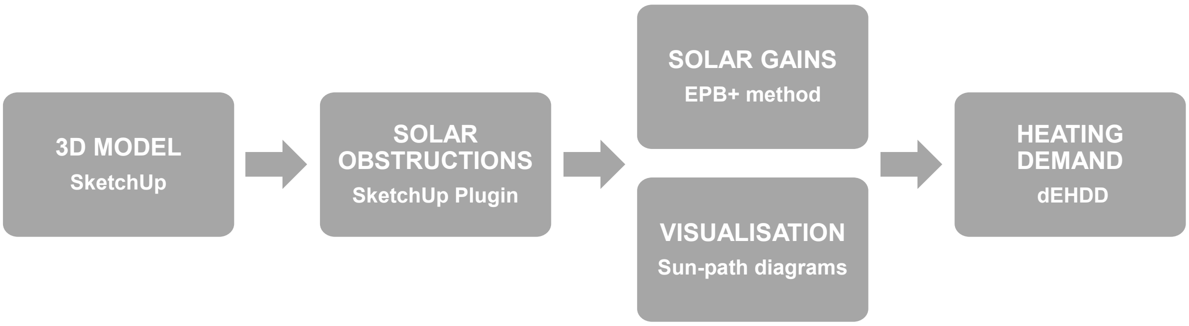

Figure 5.2: Structure of the developed design tool.

Solar gain calculations: EPB+ method

In the EPB+ method solar gains are calculated for each window as the sum of the direct, diffuse and reflected solar gains. First, direct solar gains are estimated month by month, based on a characteristic day, which is defined as the 15th day of each month. For each characteristic day, the direct solar radiation is calculated, taking into account the sun incidence angle hour by hour. The incident direct solar radiation per month on a surface j ($I_{s,dir,m,j}$) is estimated, using Formula [5.1] (Flemish Government 2017a):

$$I_{s,dir,m,j} = I_{s,dir,m,hor} \frac{Q_{s,dir,char,j}}{Q_{s,dir,char,hor}} \qquad [5.1]$$

With:

- $I_{s,dir,m,hor}$ = direct solar radiation per month on an unshaded horizontal surface, based on measurements (MJ/m²)
- $Q_{s,dir,char,j}$ = calculated direct solar radiation on a surface j with given orientation, for the characteristic day of the analysed month (J/m²day)
- $Q_{s,dir,char,hor}$ = calculated direct solar radiation on an unshaded horizontal surface for the characteristic day of the analysed month (J/m²day)

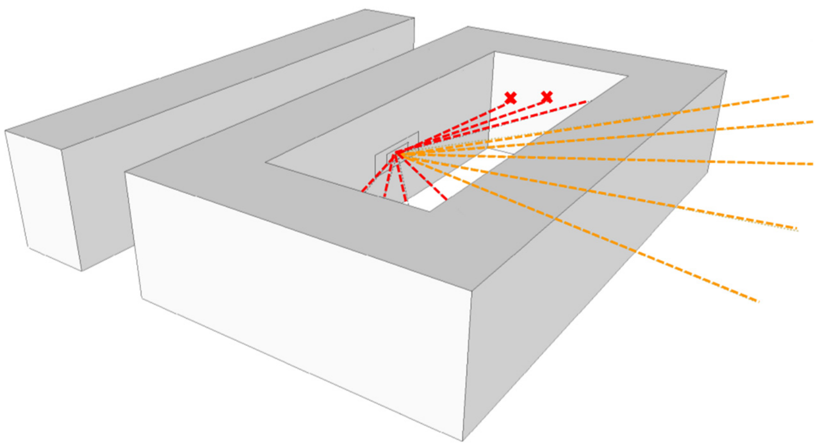

Figure 5.3: Analysis of the direct solar radiation based on the SketchUp plugin. Rays intersecting with the 3D model (red lines) correspond to hours without direct solar gains (Trigaux et al. 2015).

To evaluate the impact of solar obstructions, ray tracing techniques are used in the SketchUp 3D model (Figure 5.3). For each characteristic day of each month, rays are generated, hour by hour, starting from the central point of the analysed window and pointing to the sun. When rays intersect with the 3D model, there is no direct solar gain. The analytical outcome is a matrix, indicating the availability of direct solar radiation hour by hour for each characteristic day. This matrix is used as input for the calculation of the incident direct solar radiation on the analysed window (Trigaux et al. 2015).

Second, diffuse solar gains are calculated as proportional to the visible part of the sky dome (Sky View Factor (*SVF*)). The incident diffuse solar radiation per month on a surface j ($I_{s,dif,m,j}$) is estimated based on Formula [5.2] (Flemish Government 2017a):

$$I_{s,dif,m,j} = I_{s,dif,m,hor} \times C_m \times SVF \qquad [5.2]$$

With:

- $I_{s,dif,m,hor}$ = diffuse solar radiation per month on an unshaded horizontal surface, based on measurements (MJ/m²)
- C_m = correction factor for the anisotropic character of the diffuse solar radiation. The factor depends on the orientation and inclination of the surface.

To analyse the effect of solar obstructions based on the SketchUp 3D model, the sky dome is subdivided in x surfaces with equal area (Figure 5.4). For each surface, a ray is generated between the surface centre and the central point of the analysed window. The sky view factor is then calculated as the number of non-intersecting rays divided by the total number of analysed rays. In this dissertation, a subdivision in 3600 equal surfaces is used for simulations, leading to very accurate results (Trigaux et al. 2015).

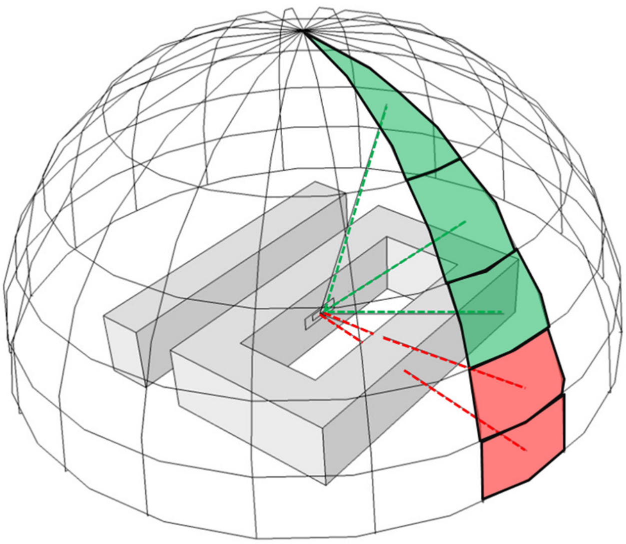

Figure 5.4: Principles for the calculation of the sky view factor using the SketchUp plugin. Green and red surfaces represent respectively the visible and invisible part of the sky dome from the centre of the window (Trigaux et al. 2015).

Third, in analogy with the original EPB method, the calculation of the reflected solar gains is limited to the reflected fraction from the ground, making an abstraction of reflections from surrounding objects. This reflected fraction is calculated as proportional to the visible part of the ground (Ground View Factor (*GVF*)) and the ground surface reflectance, for which a default value of 0.2 is used. The incident reflected solar radiation per month on a surface j ($I_{s,refl,m,j}$) is estimated based on Formula [5.3] (Flemish Government 2017a):

$$I_{s,refl,m,j} = 0.2 \times I_{s,tot,m,hor} \times GVF \text{ , where } GVF = \left(\frac{1 - \cos \vartheta_j}{2} \right) \qquad [5.3]$$

With:

- 0.2 = ground surface reflectance factor
- $I_{s,tot,m,hor}$ = total solar radiation per month on an unshaded horizontal surface, based on measurements (MJ/m²)
- ϑ_j = surface inclination compared to a horizontal surface (°)

In contrast to the direct and diffuse solar radiation, the impact of shading patterns on the ground, reducing ground solar reflection is not considered in the EPB+ method. The amount of reflected solar radiation is thus identical in shaded and unshaded conditions. A more detailed calculation of the reflected solar gains, including reflections from neighbouring buildings and the impact of shading patterns on the ground, would require more complex reflection algorithms. Due to the small contribution of reflected radiation to the total solar gains, this simplification however influences the global results to a small extent (Trigaux et al. 2015).

The 3D model furthermore allows to extract data on solar obstructions for visualisations. This is done, by drawing vertical planes through the centre of the analysed window, in 36 directions, in steps of 10°. Obstruction angles are then derived based on the intersection lines with the 3D model. Via those angles the programme visualises obstructions on sun-path diagrams (Figure 5.5).

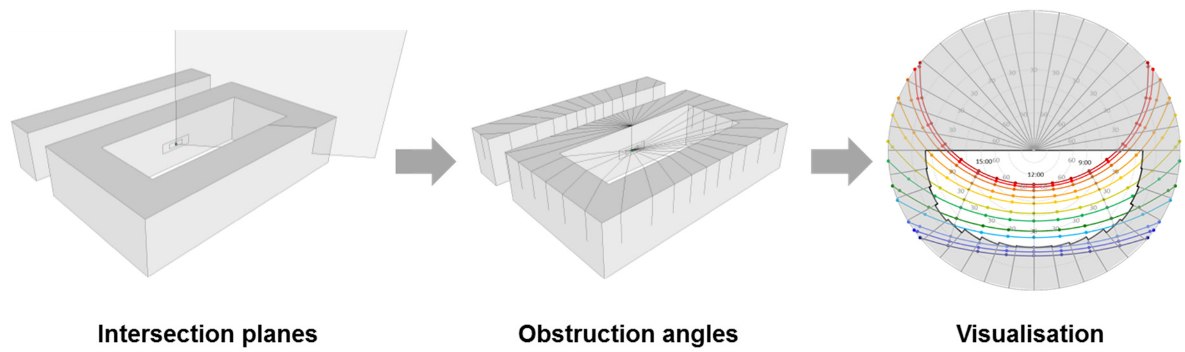

Figure 5.5: Extraction of data on solar obstructions, based on the SketchUp plugin. The data are used for visualisations on sun-path diagrams.

Heating energy demand: dynamic Equivalent Heating Degree Day (dEHDD) method

The dEHDD method (Trigaux et al. 2014) is a refinement of the existing EHDD method to estimate the heating energy demand in buildings (DPWB 1984a; DPWB 1984b). The basic assumption of the EHDD method is that the yearly heating energy demand is proportional to the number of yearly Equivalent Heating Degree Days (EHDD). The number of EHDD takes into account how efficiently the building makes use of the internal heat gains and solar gains and is calculated for each month of the heating season based on the difference between two temperatures: the temperature of no more heating (T_{NH}) and the temperature without heating (T_{WH}). This is illustrated in Figure 5.6 for the moderate Belgian climate[4].

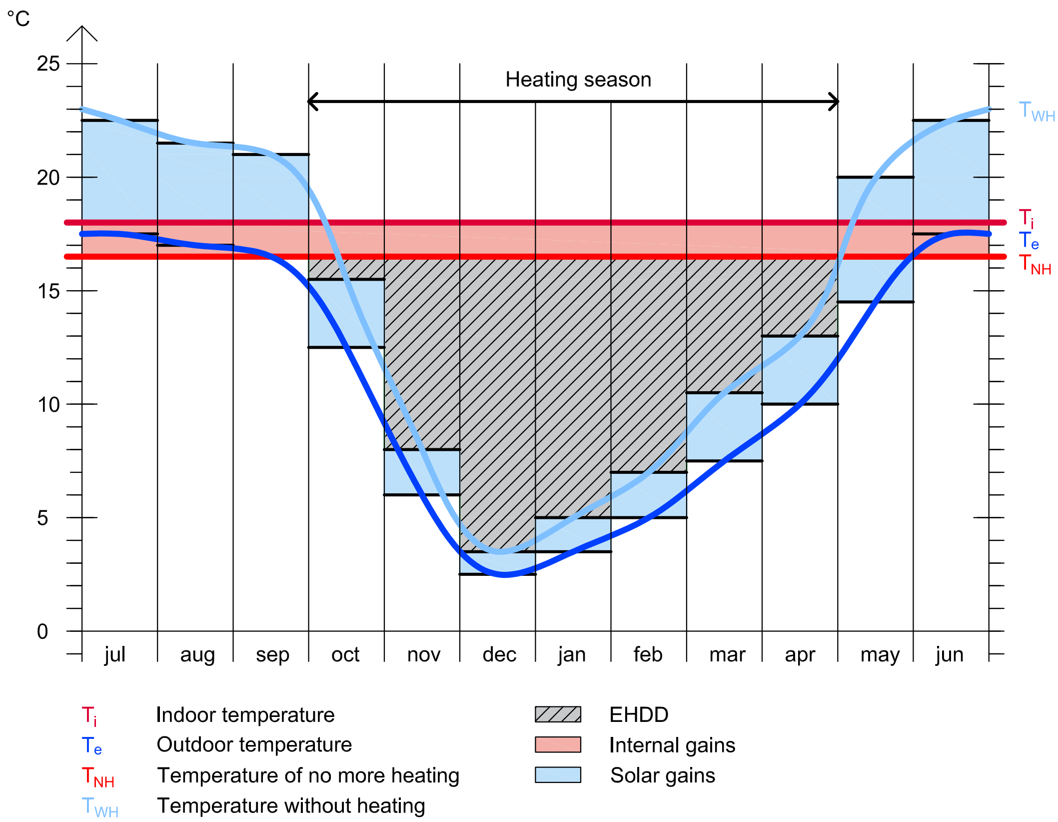

Figure 5.6: Equivalent Heating Degree Days for the moderate Belgian climate, based on (DPWB 1984a; DPWB 1984b).

The first temperature (T_{NH}) is defined as the indoor temperature above which no heating is required. This T_{NH} is lower than the average indoor temperature (T_i), as the internal heat gains, resulting from people, appliances and artificial lighting, compensate a part of the heat losses. In this research, a fixed average indoor temperature (T_i) of 18°C is considered, taking into account fluctuations between day and night temperature set points and space temperature differences between heated and unheated spaces. Furthermore, the internal heat gains in

[4] For the calculations, the reference climate data for Brussels (Uccle) are used, as defined in the EPB regulation (Flemish Government 2017a).

residential buildings are calculated as proportional to the heated volume of each housing unit, based on Formula [5.4][5] (Flemish Government 2017a):

$$Q_{IHG} = 0.67 \times V + 220 \quad [5.4]$$

With:

- Q_{IHG} = internal heat gains (J/s)
- V = heated volume (m³)

The second temperature (T_{WH}) is the indoor temperature, resulting from solar gains, when the building is not heated and not occupied but loses energy via transmission and ventilation. This T_{WH} is higher than the average outdoor temperature (T_e), as solar gains result in an increase of the indoor temperature. To assess the impact of solar gains, several approaches are possible, ranging from static to dynamic simulations. In the original EHDD method, a static approach was followed, based on average solar radiation data (DPWB 1984a; DPWB 1984b). In the dEHDD method, a more accurate estimation of the impact of solar gains is proposed based on the EPB method or the refined EPB+ method (Trigaux et al. 2014). In a recent publication (Trigaux et al. 2015), the original EPB method and the EPB+ method were compared with EnergyPlus dynamic simulations, based on a case study. While the original EPB method lacked sufficient accuracy to estimate the impact of shading patterns, the EPB+ method was found to yield results comparable to EnergyPlus. The EPB+ method is therefore selected as the most appropriate for this research.

Based on the number of dEHDD, the yearly heating energy demand is estimated using Formula [5.5], which includes the transmission losses through the building skin and ventilation losses (DPWB 1984a; DPWB 1984b):

$$Q_{H,net} = \left(U_m \times S + V \times n \times 0.36\right) \times 3600 \times 24 \times 10^{-6} \times dEHDD \quad [5.5]$$

With:

- $Q_{H,net}$ = yearly energy demand for heating (MJ)
- U_m = average heat transfer coefficient (W/m²K)
- S = heat loss surface (m²)
- V = heated volume (m³)
- n = total air change per hour (1/h), resulting from both controlled ventilation and (uncontrolled) air infiltration
- $dEHDD$ = number of dynamic Equivalent Heating Degree Days

[5] This formula includes a variable term, proportional to the heated volume, and a fixed term to account for the fact that internal gains are relatively higher in small housing units. The formula is only applicable to housing units with a heated volume of more than 192m³ (This is the case for all housing units analysed in this research).

Because of the limited number of input data, the dEHDD method is very useful in the early design stages, such as the master planning of neighbourhoods. Moreover the number of dEHDD can be used as an indicator to compare the utilization of solar gains in various building layouts.

From heating energy demand to heating energy use

The heating energy use can be calculated by dividing the heating energy demand by the global efficiency of the heating system, based on Formula [5.6] (VEA 2013):

$$Q_{H,final} = \frac{Q_{H,net}}{\eta_{H,global}} \qquad [5.6]$$

With:

- $Q_{H,final}$ = yearly energy use for heating (MJ)
- $\eta_{H,global}$ = global efficiency of the heating system

In this research a number of representative heating systems are defined, ranging from old to current technical systems (see Chapter 8). The global efficiency of those systems is estimated based on Formula [5.7], using the default values defined in the Flemish standards for Energy Performance Certificates (EPC) (VEA 2013):

$$\eta_{H,global} = \eta_{H,prod} \times \eta_{H,distr} \times \eta_{H,em} \times \eta_{H,contr} \qquad [5.7]$$

With:

- $\eta_{H,prod}$ = efficiency of heat production
- $\eta_{H,distr}$ = efficiency of heat distribution
- $\eta_{H,em}$ = efficiency of heat emission
- $\eta_{H,contr}$ = efficiency of control mechanisms

5.1.2 Energy use for domestic hot water

In accordance with the methodology proposed by the Passivhaus Projektierungs Paket (PHPP), the yearly energy demand for domestic hot water is assumed to be proportional to the number of inhabitants, based on Formula [5.8] (Feist et al. 2001):

$$Q_{HW,net} = C_{HW} \times (T_{HW} - T_{CW}) \times 4.186 \times 365 \times 10^{-3} \times P \qquad [5.8]$$

With:

- $Q_{HW,net}$ = yearly energy demand for domestic hot water (MJ)
- C_{HW} = consumption of domestic hot water (l/person/day), default = 25 l/person/day
- T_{HW} = temperature of domestic hot water (°C), default = 60°C
- T_{CW} = temperature of cold water supply (°C), default = 10°C
- P = number of inhabitants

The yearly energy use for domestic hot water can then be calculated using Formula [5.9] (VEA 2013). As for the heating system, the efficiency values and heat losses for storage related to the hot water system are based on the EPC standards (VEA 2013).

$$Q_{HW,final} = \frac{\dfrac{Q_{HW,net}}{\eta_{HW,distr}} + Q_{HW,stor}}{\eta_{HW,prod}} \qquad [5.9]$$

With:

- $Q_{HW,final}$ = yearly energy use for domestic hot water (MJ)
- $\eta_{HW,distr}$ = efficiency of heat distribution
- $Q_{HW,stor}$ = heat losses from hot water storage (MJ)
- $\eta_{HW,prod}$ = efficiency of heat production

5.1.3 Energy use for ventilation

The energy use for ventilation consists of the electricity consumption of the ventilators in case of mechanical ventilation and is calculated as proportional to the heated volume, based on Formula [5.8] (VEA 2013):

$$Q_V = p_V \times V \times 3600 \times 24 \times 365 \times 10^{-6} \qquad [5.10]$$

With:

- Q_v = yearly energy use for ventilation (MJ)
- p_v = ventilator power per unit volume (W/m³), p_V is equal to 0.125 W/m³ for mechanical exhaust ventilation and 0.235 W/m³ for mechanical supply and exhaust ventilation
- V = heated volume (m³)

5.1.4 Energy use for lighting and appliances

The energy use for lighting[6] and appliances in buildings is estimated based on an average electricity consumption of 3500 kWh/year for households of three people in Belgium (VREG 2017). A more detailed calculation was not implemented as the electricity consumption depends on the selected type of lighting and appliances which are very often not designer but rather user related decisions.

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[6] The impact of the availability of daylight on the energy use for artificial lighting is not considered in this research. It should be investigated in further research whether a similar approach to the solar gain calculations can be used to estimate the availability of daylight in buildings. However the energy use for artificial lighting is reduced importantly when using high performance lighting compared to incandescent lighting which was common practice till recently.

Next to the electricity consumption in buildings, the electricity consumption for road lighting is also included in the analysis of the impact of the road infrastructure. This is further elaborated in Chapter 7.

When a photovoltaic (PV) system is installed, the electricity production is subtracted from the total electricity consumption. The electricity production from a PV system (W_{pv}) is estimated based on Formula [5.11] (Flemish Government 2017a):

$$W_{pv} = \frac{P_{pv} \times RF_{pv} \times c_{pv} \times I_{s,tot,pv}}{1000} \quad [5.11]$$

With:

- W_{pv} = yearly electricity production from the photovoltaic system (MJ)
- P_{pv} = peak power of the photovoltaic system (Wp) at a nominal radiation of 1000 W/m²
- RF_{pv} = reduction factor of the photovoltaic system, default = 0.75
- C_{pv} = correction factor for shading effects, C_{pv} is equal to 1 when there is no shading obstacle
- $I_{s,tot,pv}$ = total solar radiation per year on the surface of the photovoltaic system, taking into account shading effects (MJ/m²)[7]

5.1.5 Impact of energy use

The environmental and financial impact of operational energy use is calculated by multiplying the energy use per contributor (i.e. heating, domestic hot water, ventilation, lighting and appliances) with the environmental and financial impact of the selected energy source. The environmental and financial data used for the energy sources are described in the subsequent paragraphs.

Environmental impact of energy sources

The environmental impact per energy source, expressed in euro per MJ, is shown in Figure 5.7. The data are based on records from the database Ecoinvent version 2.2 (Frischknecht et al. 2007), but adjusted to improve their representativeness for the Belgian context.

For the electricity use, the Belgian production mix is selected which includes the impact of the electricity production, electricity network and network losses. This record is compared with specific data for the production mix of the Belgian energy provider Electrabel, based on (Allacker 2010).

[7] Shading effects on solar panels are not considered in this research as the buildings in each analysed neighbourhood model are of the same height (see Chapter 8). As a result, there is no shading of the flat roof areas by surrounding buildings. Furthermore, minimum spacing distances are applied between the solar panels to avoid shading effects.

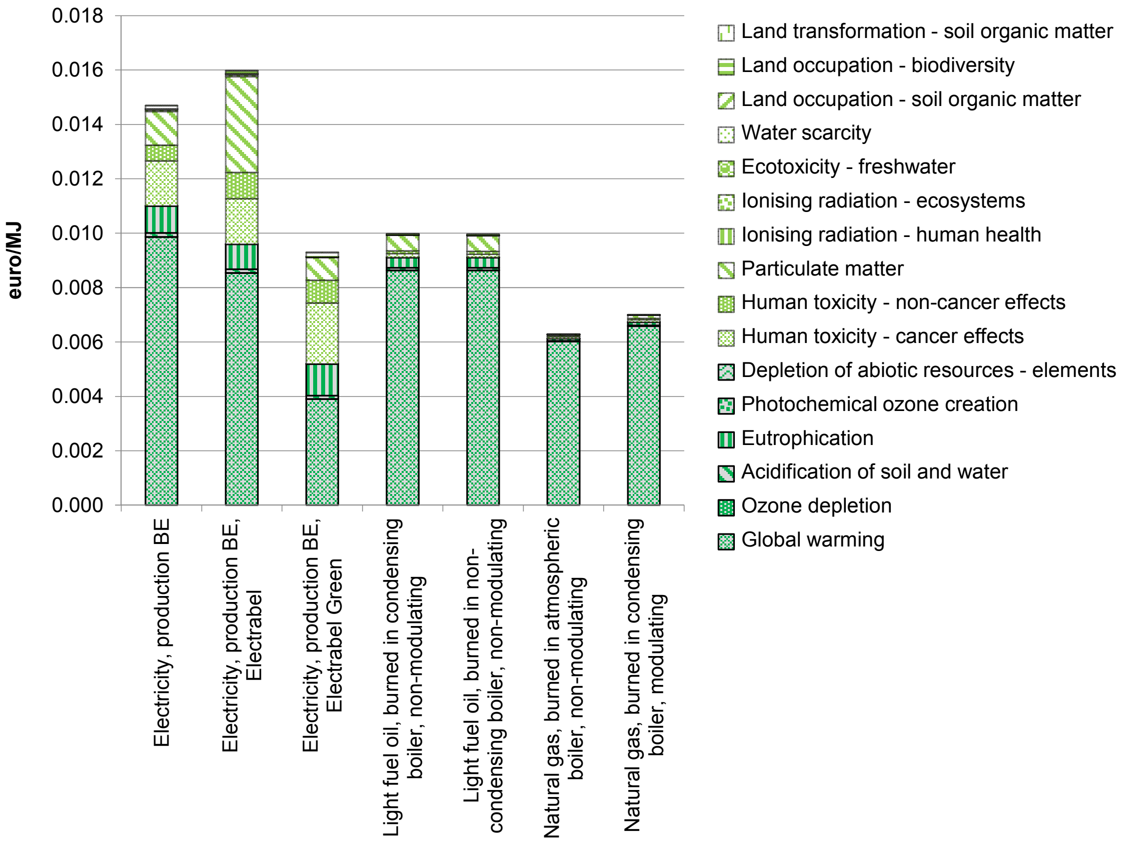

Figure 5.7: Environmental cost of energy sources.[8]

For natural gas and light fuel oil, Ecoinvent provides LCI data[9] for the combustion processes including the impact of the fuel, emissions and waste from combustion, boiler electricity consumption and technical components (e.g. boiler, oil storage). In this research, the Swiss data records are adapted to the Belgian context by replacing the impact of the fuel and boiler electricity consumption by Belgian (or European[10]) corresponding processes. Furthermore, technical components are excluded from the LCI data records as these are already included in the assessment of the building elements.

Significant differences are noticed between the environmental impact of the various energy sources (Figure 5.7). Compared to the Belgian electricity mix, the environmental impact of light fuel oil and natural gas burned in a condensing boiler is about 30% and 50% lower respectively. The impact of electricity can however vary importantly depending on its production mix. The impact of the green electricity mix from Electrabel is for example about 40% lower than the impact of the standard electricity mix from the same energy provider.

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[8]By convention, the environmental impact of oil and natural gas in Ecoinvent is expressed per MJ, based on the lower heating value of these fuels.

[9] The impact of the conversion and distribution losses is taken into account in the Ecoinvent data. A quantification of primary energy is therefore not needed.

[10] For the impact of “Light fuel oil, at regional storage”, a European process is selected as no Belgian process is available in Ecoinvent.

Financial impact of energy sources

The financial cost per energy source, expressed in euro per MJ, is shown in Figure 5.8. The average energy prices are based on data from the Belgian energy regulator (CREG 2015) and Belgian statistics (Belgian Federal Government 2017a). For the electricity use, no distinction is made between a standard and green electricity mix as there is no indication for substantial price differences[11]. As for the environmental impact, significant differences in financial cost are noticed between the energy sources. Compared to electricity, the financial cost of light fuel oil and natural gas is about 75% and 70% lower respectively.

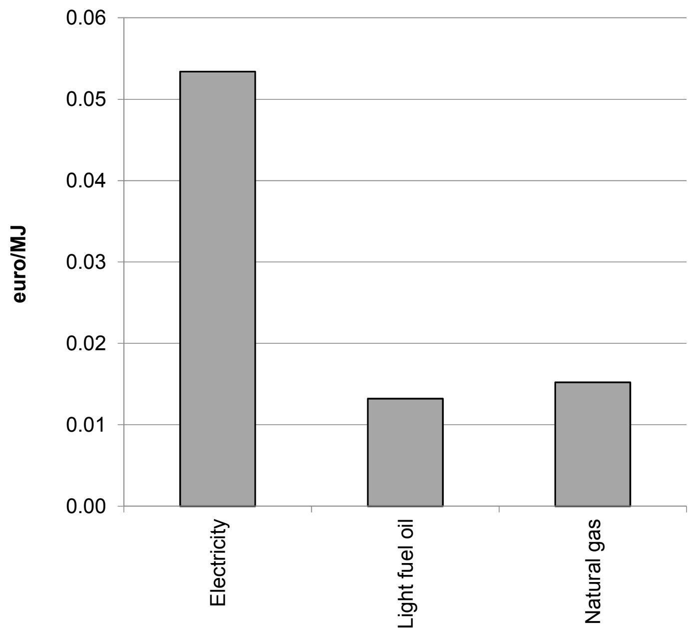

Figure 5.8: Average prices for energy sources in 2015 in Belgium, based on (CREG 2015; Belgian Federal Government 2017a). The average prices are expressed as consumer prices (excluding VAT).[12]

5.2 Operational water use

Besides the industrial sector, households are one of the main users of water. In 2012, households contributed to about 40% of the total water use and 60% of the tap water use in Flanders (VMM 2017a). The impact of operational water use should therefore be included when assessing the sustainability of residential neighbourhoods.

Various tools are available to estimate the water input and output flows during the operation of buildings and/or neighbourhoods. For example, the LCA tools novaEQUER and GreenCalc+[13] both include a specific water calculation module (Stichting Sureac 2013; IZUBA énergies 2017).

[11] Price differences are rather noticed between energy providers and not depending on the type of electricity mix.

[12] As for the environmental impact, the financial cost of oil and natural gas is expressed per MJ, based on the lower heating value of these fuels.

[13] The development of GreenCalc+ has been stopped. This LCA-tool is therefore no more publicly available.

While GreenCalc+ only assesses the impact from the tap water consumption, novaEQUER also covers the impact resulting from wastewater and rainwater discharge.

In this dissertation, an existing water calculation tool is used, which was developed by the Belgian Building Research Institute (BBRI) and included in the Flemish sustainability assessment tool for dwellings "Vlaamse Maatstaf voor Duurzaam Wonen en Bouwen" (Flemish Government 2011). The BBRI tool was chosen for four reasons. First, it includes both an estimation of the tap water consumption and the amount of waste water and rainwater discharge. Second, the tool allows both a detailed and a simplified calculation based on def ault values for the water using appliances and fixtures. The latter is particularly appropriate for the master planning stage of neighbourhoods when detailed input data are lacking. Third, the BBRI tool was developed for the Belgian context, including specific default values for water consumption and yearly rainfall. Finally, the tool is available in an Excel spreadsheet which can be easily integrated in the Excel calculation model developed in this research (see Chapter 6).

5.2.1 Tap water consumption

The tap water consumption in dwellings is calculated as the difference between the total water consumption and the volume of reused greywater[14] and rainwater, based on Formula [5.12] (Flemish Government 2011):

$$C_{TW} = C_{W,tot} - V_{GW,reuse} - V_{RW,reuse} \qquad [5.12]$$

With:

- C_{TW} = consumption of tap water (l/day)
- $C_{W,tot}$ = total water consumption (l/day). The total water consumption is estimated based on the amount and type of water using appliances and fixtures and the number of inhabitants per household. In this research, standard appliances and fixtures are selected resulting in an average water use of 435 litre per day for a household of 4 people (Table 5.1).
- $V_{GW,reuse}$ = volume of reused greywater (l/day). The volume of reused greywater depends on the available volume of wastewater from sinks, showers, baths and washing machines and on the appliances connected to the treated greywater system. In this research, the reuse of greywater is not considered for the assessment of the schematic neighbourhood models ($V_{GW,reuse}$ = 0).
- $V_{RW,reuse}$ = volume of reused rainwater (l/day). The volume of reused rainwater depends on the size of the rainwater pit, the roof surfaces used for rainwater harvesting and the appliances connected to the rainwater pit[15].

[14] Greywater is slightly polluted wastewater from sinks, showers, baths and washing machines. Greywater can be treated on site and reused for non-potable water use such as toilet flushing or garden irrigation.

[15] The detailed calculation of the volume of reused rainwater is described in the BBRI tool (Flemish Government 2011).

Table 5.1: Default values for the daily tap water consumption in a household of 4 people (Flemish Government 2011).

Appliances and fixtures	Water use (l/day)
Bathroom tap	24
Kitchen tap	20
Toilet tap	36
Toilet	144
Bath	24
Shower	126
Washing machine	45
Laundry tap	11
Garden irrigation	5
Total per household	**435**
Total per person	**109**

5.2.2 Wastewater and rainwater discharge

The built environment is responsible for the discharge of two types of water flows: wastewater and rainwater from roofs and paved areas. First, wastewater from appliances and fixtures is collected in the sanitary sewer in order to be treated in a wastewater treatment plant. The volume of discharged wastewater from dwellings is calculated as the difference between the total volume of generated wastewater and the volume of reused greywater, based on Formula [5.13] (Flemish Government 2011):

$$V_{WW,dis} = V_{WW,tot} - V_{GW,reuse} \qquad [5.13]$$

With:

- $V_{WW,dis}$ = volume of wastewater discharged (l/day)
- $V_{WW,tot}$ = total volume of generated wastewater (l/day). The total volume of generated wastewater is assumed to be equal to the total water consumption ($C_{W,tot}$).

Second, rainwater from roofs and paved areas can be drained in three ways. A first option is to discharge rainwater into a combined sewer. In Flanders this option is only allowed when a separate sewer (including a storm and sanitary sewer) is not available in the street. In that case rainwater is transported together with wastewater to the wastewater treatment plant, resulting in an additional impact for the wastewater treatment. The second and third options are respectively to discharge rainwater into the storm sewer or an on-site infiltration system. For those options, outside the impact for the provision of the storm sewer or infiltration system, no additional impact has to be calculated as there is no treatment of rainwater.

For each roof surface, the volume of discharged rainwater is estimated based on Formula [5.14] (Flemish Government 2011):

$$V_{RW,roof,dis} = (A_{roof,hor} \times i \times m_{roof} \times RF)/365 - V_{RW,reuse} \qquad [5.14]$$

With:

- $V_{RW,roof,dis}$ = volume of discharged rainwater from a roof surface (l/day)
- $A_{roof,hor}$ = horizontal projected roof surface (m^2)
- i = inclination coefficient, depending on the roof inclination and orientation (i = 1 for flat roofs[16])
- m_{roof} = run-off coefficient, depending on the type of roof surfacing material (m_{roof} = 0.75 for a bituminous flat roof[17])
- RF = average yearly rainfall (l/m^2 horizontal surface). The average yearly rainfall in Belgium is equal to 829 l/m^2 horizontal surface

For each paved area, the volume of discharged rainwater is estimated based on Formula [5.15] (Flemish Government 2011):

$$V_{RW,paved,dis} = (A_{paved} \times m_{paved} \times RF)/365 \qquad [5.15]$$

With:

- $V_{RW,paved,dis}$ = volume of discharged rainwater from a paved area (l/day)
- A_{paved} = surface of paved area (m^2)
- m_{paved} = run-off coefficient, depending on the type of surfacing material (m_{paved} = 0.85 for asphalt pavement and 0.7 for clinker pavement[18])

5.2.3 Impact of water use

The environmental and financial impact of operational water use is calculated by multiplying the tap water consumption and the volume of discharged wastewater and rainwater[19] with their respective environmental and financial impact. The environmental and financial data used for tap water and wastewater treatment are described in the subsequent paragraphs.

[16] Values for other roof inclinations and orientations can be found in the table included in the BBRI tool (Flemish Government 2011).

[17] Values for other types of roof surfacing material can be found in the table included in the BBRI tool (Flemish Government 2011).

[18] Values for other types of surfacing material can be found in the table included in the BBRI tool (Flemish Government 2011).

[19] As mentioned above, only the volume of rainwater discharged to a combined sewer has to be considered for the impact assessment.

Environmental impact of tap water and wastewater treatment

The environmental impact data for tap water and wastewater treatment (Figure 5.9) are based on LCI data from Ecoinvent version 2.2 (Frischknecht et al. 2007). The Ecoinvent record for tap water includes not only the impact of the water resources but also the impact of the transportation network (to the treatment plant) and energy use for water treatment. Concerning wastewater treatment, the data record covers the treatment process and necessary infrastructure, i.e. the sewer network and treatment plant. As shown in Figure 5.9, the environmental impact of wastewater treatment is about nine times higher than the impact of tap water. It is therefore expected that wastewater and rainwater discharge will be the main contributor to the total environmental impact of operational water use (see Chapter 8).

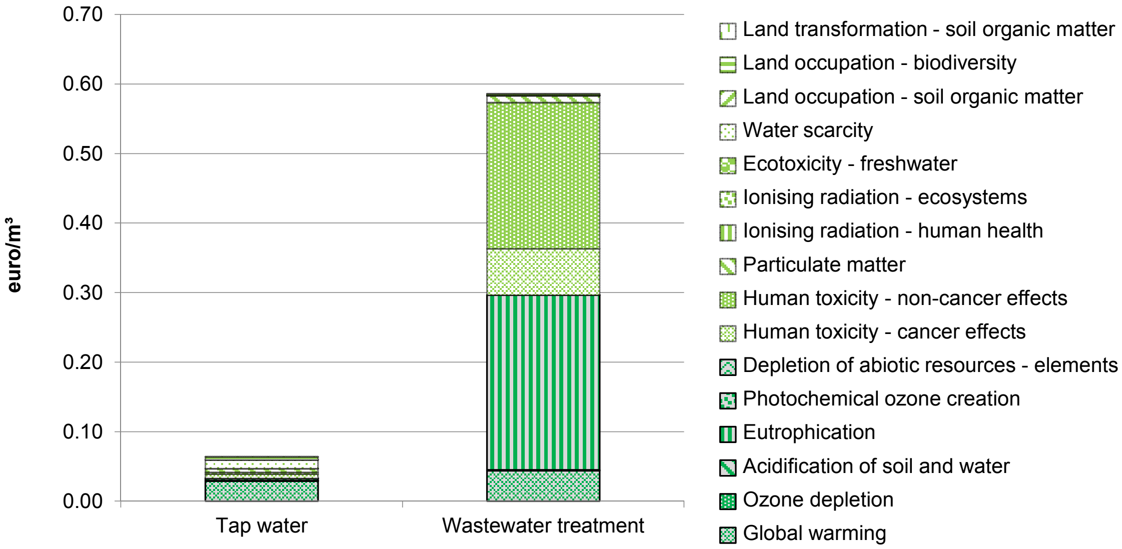

Figure 5.9: Environmental cost of tap water and wastewater treatment.

Financial impact of tap water

The price for tap water, is calculated as the Flemish average of the water price per municipality[20], collected from the website of the Flanders Environment Agency (VMM 2015). In contradiction to the environmental impact, there is no separate financial cost for waste water treatment. This cost is directly included in the tap water price via a number of taxes, which account for about 60% of the total tap water price (VMM 2015) .

Table 5.2: Average price for tap water in 2015 in Flanders, based on (VMM 2015).

	Price (€/m³) - excluding VAT
Distribution of tap water	1.61
Taxes for wastewater treatment	2.73
Total	**4.35**

[20] The size of the population per municipality is not considered for the calculation of the Flemish average. The water price is calculated for a household with three people and a yearly tap water consumption of 104 m³/year.

5.3 Primary land use

Urban sprawl and the increase of the built-up area have a major impact on land use. Between 1980 and 2000, the built-up area in Europe increased by about 20% (European Environment Agency 2006). Neighbourhoods are responsible for two types of land use interventions: primary land use, i.e. the neighbourhood spatial footprint and secondary land use, associated with the resource extraction, production, transport and end-of-life treatment of construction products (Allacker et al. 2014) and the operational energy use, operational water use and user transport.

While secondary land use is already assessed in the SuFiQuaD and MMG E-LCA method (Allacker et al. 2013a; Allacker et al. 2013b; De Nocker and Debacker 2015), the environmental impact related to the primary land use is not considered. This is also the case in most current LCA studies of the built environment. In (Allacker et al. 2014), the primary land use of a detached house in Belgium is evaluated, using different land use impact assessment models. This study reveals the importance of including primary land use in a building LCA, as the impact of primary and secondary land use are of the same order of magnitude.

In this section a method is proposed to assess the environmental and financial impact of primary land use in neighbourhoods, considering the footprint of buildings, infrastructure and open spaces. This method was presented at the SBE16 conference in Thessaloniki (Trigaux et al. 2017a).

5.3.1 Environmental impact of primary land use

Land use impact indicators and monetary values

In the MMG E-LCA method (Allacker et al. 2013b; De Nocker and Debacker 2015), land use impacts are assessed, considering two types of interventions: land occupation and land transformation. Land occupation occurs when a specific land use type is maintained over a period of time, leading to a delay in the recovery of land to its potential natural state, while land transformation refers to a change in the land use type (Allacker et al. 2014). Impacts related to land occupation and transformation are evaluated based on a combination of two impact assessment methods, such as recommended by (Allacker et al. 2014): soil organic matter (SOM) of (Milà i Canals et al. 2007) for the impacts on soil quality and Eco-indicator 99 (Goedkoop and Spriensma 2000) for the impacts on biodiversity (Table 5.3).

As mentioned in Chapter 3, the characterised environmental impact indicators can be translated to environmental costs, by multiplying them with their specific monetary value. Concerning the valuation of land use impacts (Table 5.3), MMG monetary values are provided for the impacts on soil organic matter, both for land occupation and land transformation. For the impacts on biodiversity, MMG monetary values are only available for land occupation, based on impacts expressed in square metres times year (m^2a) and a subdivision in three land use categories: urban, agricultural and forest land use. As the MMG monetary values for the impacts on biodiversity are not linked to the loss of species, calculated in Eco-indicator 99, an alternative valuation method, such as defined in (Allacker 2010), is proposed, based on the impacts expressed in PDF (Potentially Disappeared Fraction of species). In Chapter 8, a comparison is made between the E-LCA results based on the original set of MMG monetary values, further referred to as MMG, and the alternative set of monetary values, further referred to as MMG_PDF (see Table 5.3).

Table 5.3: Land use impact indicators and their monetary values. Two scenarios for the monetary values are considered: MMG (central scenario for Western Europe) and MMG_PDF (Allacker 2010; De Nocker and Debacker 2015).

CEN + indicators	Unit	MMG (€/unit)	MMG_PDF (€/unit)
Land occupation - soil organic matter	kg C deficit	2.7E-06	2.7E-06
Land occupation - biodiversity	PDF*m²a		0.49
Urban	m²a	0.30	
Agricultural	m²a	6.0E-03	
Forest	m²a	2.2E-04	
Land transformation - soil organic matter	kg C deficit	2.7E-06	2.7E-06
Land transformation - biodiversity	PDF*m²		0.49

Land use impact assessment

When assessing the environmental impact of primary land use in neighbourhoods, a distinction can be made between three interventions (Figure 5.10). First, a transformation in type of land use (from A to B), such as for example from forest to urban land use, can occur at the start of the neighbourhood life cycle (T_1). This transformation leads to a decrease or increase in land quality[21], depending on the original type of land use. The transformation impact (TI_{land}) is calculated as the difference in land quality between the original state and the neighbourhood land use, multiplied by the land use area (Formula [5.16]).

$$TI_{land} = (LQ_A - LQ_B) \times A_{land} \qquad [5.16]$$

With:

- LQ_A = land quality of original state (A)
- LQ_B= land quality of neighbourhood land use (B)
- A_{land} = land use area (m²)

Second, a specific type of land use is maintained during the neighbourhood life span (from T_1 to T_2), leading to an occupation impact. This occupation impact (OI_{land}) is calculated as the difference in land quality between the neighbourhood land use and the (reference) natural state, multiplied by the land use area and neighbourhood life span (Formula [5.17]).

[21] In this research, land quality is defined in terms of impacts on soil quality and biodiversity (see selected land use impact indicators).

$$OI_{land} = (LQ_B - LQ_{ref}) \times A_{land} \times (T_2 - T_1) \quad [5.17]$$

With:

- LQ_{ref} = land quality of (reference) natural state
- T_1 = start of the neighbourhood life cycle (year)
- T_2 = end of the neighbourhood life cycle (year)

Third, a transformation in type of land use (from B to C), such as for example from urban land to meadow, can occur at the end of the neighbourhood life cycle (T_2). To avoid double counting, this transformation impact should be allocated to the next life cycle and is therefore not considered within this research.

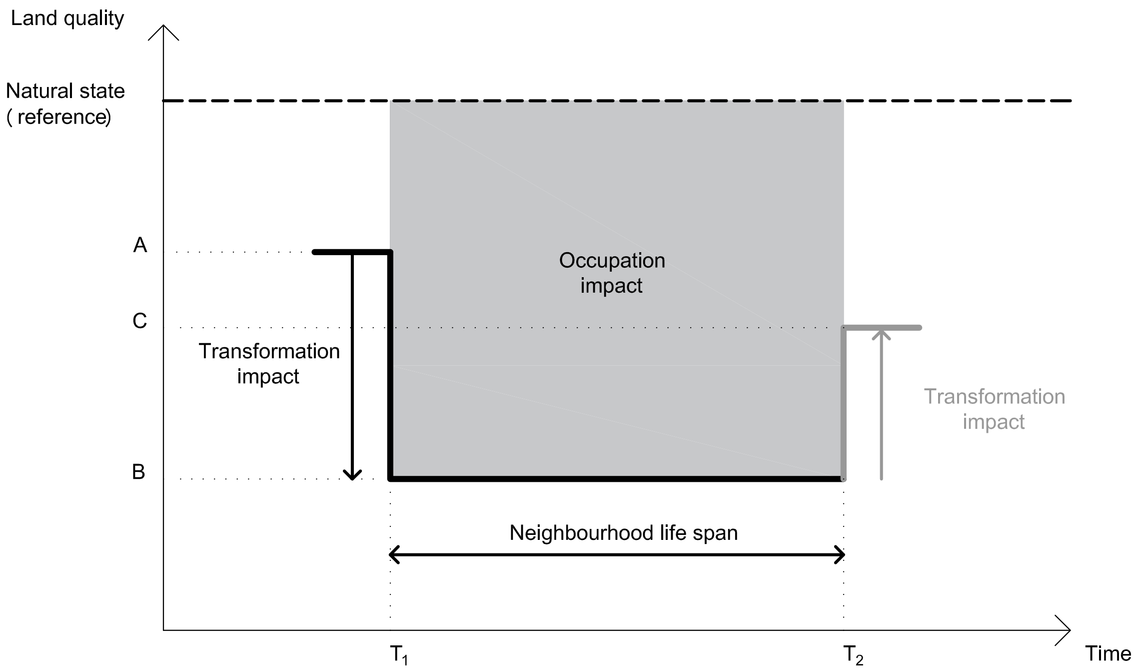

Figure 5.10: Land use interventions in neighbourhoods, based on (van der Voet 2001).

5.3.2 Financial impact of primary land use

The financial impact of primary land use is limited to the initial cost for land purchase. Land occupation taxes during the neighbourhood life cycle are not assessed due to a lack of statistical data on the cadastral income, which is used for the calculation of taxes on immovable property[22]. Furthermore, income arising from the sale of the land at the end of the life span is not considered as it should be assigned to module "D: Reuse, recovery, recycling potential", which falls outside the system boundaries (CEN 2015) (see Chapter 3).

[22] In Belgium taxes on immovable property are calculated based on the cadastral income for the reference year 1975 (Flemish Government 2017b). Statistical data on the cadastral income depending on the location and type of property are not available.

Concerning the cost for land purchase, building land prices based on Belgian statistics are used (Belgian Federal Government 2017b). As data are only available until year 2014, prices for the year 2015 are extrapolated based on the average building land price evolution between 2005 and 2014. As default value for the calculations, the average building land price in Flanders is selected (187.79 euro/m² - excluding taxes)[23]. However, as high variations are noticed depending on the municipality (Table 5.4), a sensitivity analysis is done based on the quartile values (see Chapter 8).

Regarding the taxes on land purchase, VAT or registration fees can be applied. In this research, it is assumed that the land and the new buildings are sold by the same property developer. In that case a VAT rate of 21% is applied to the land prices (Flemish Government 2017c).

Table 5.4: Quartile values of the average building land price in Flemish municipalities (extrapolated prices for the year 2015), based on (Belgian Federal Government 2017b).

Quartile	**Municipality**	**Price for building land (€/m²) - excluding taxes**
Minimum	Ronse	80.30
First quartile	Erpe-Mere	147.97
Median	Boortmeerbeek	185.54
Third quartile	Schelle	235.63
Maximum	Knokke-Heist	1161.18
Flemish average	-	187.79

5.4 User transport

The transport sector is responsible for major environmental impacts. In 2014 this sector contributed to 14% of the total energy use and 22% of the total greenhouse gas emissions in Flanders (VMM 2017b). As the spatial structure and urban density influence transport means, trips and distances, user transport should be included when assessing the impact of neighbourhoods.

In this section, a simplified approach is developed to assess the impact of user transport in neighbourhoods in the Belgian/Flemish context, taking into account the influence of characteristics of the built environment, such as accessibility, public transport and cycling infrastructure. This approach is more comprehensive than the rough estimations of the impact of user transport, which are included in the SuFiQuaD research project (Allacker 2010; Allacker et al. 2013a).

[23] Large differences in average building land prices are noticed between the more urbanized Flemish region (187.79 euro/m²) and more rural Walloon region (53.08 euro euro/m²). To insure the consistency with the statistical data on user transport, which are only available for Flanders, the average building land price for Flanders is selected as default, instead of the Belgian average (126.01 euro/m²).

Figure 5.11: Assessment steps to estimate the impact of user transport in neighbourhoods.

As shown in Figure 5.11, the assessment is composed of three main steps. First, a reference transport profile is defined based on statistical data on average transport distances per transport mode in Flanders. Second, a site specific transport profile is calculated for the analysed neighbourhood by multiplying the reference transport distances with corrections factors depending on the built environment characteristics. Third, the impact of user transport is calculated by multiplying the corrected transport distances with the impact per transport mode. The different steps are explained in more detail in the subsequent sections.

5.4.1 Reference transport profile

The reference transport profile is based on statistical data from the most recent Research on Transport Behaviour in Flanders ("Onderzoek VerplaatsingsGedrag (OVG) Vlaanderen" - version 5.1) (Declercq et al. 2016). In this study, average number of trips and transport distances per person[24] per day are reported for the various transport modes (Table 5.5). For the definition of the reference transport profile, the categories "Moped", "Motorcycle" and "No answer" are not further considered as they have a low contribution (less than 0.2%) to the transport distances. Furthermore, the categories "Coach" and "Other" (including transport by plane) are not taken into account as they include occasional transport modes rather than transport modes for daily mobility, and are seen as independent of urban planning decisions. When looking at the limited set of categories (Table 5.5), the average Flemish transport profile is dominated by car transport which contributes to more than 70% of the total number of trips and more than 85% of the total transport distances.

Besides average transport data, the Research on Transport Behaviour in Flanders also includes data for the different areas defined in the Structure Plan Flanders (Figure 5.12) (Declercq et al. 2016). Important differences are noticed between the areas, with lower total transport distances in urban areas compared to the rural area. For example, the total transport distances in the metropolitan urban area (central municipalities) is 30% lower than in the rural area. Furthermore the share of public transport is higher in urban areas. In the metropolitan urban area (central municipalities), public transport is used for 16% of the transport distances, compared to 8% in the rural area. This confirms the influence of the spatial structure on the impact of transport.

[24] Only people older than 6 are included in the OVG study.

Table 5.5: Average transport profile in Flanders, including the daily number of trips and transport distances per person (Declercq et al. 2016). The last five categories (indicated in grey) are not considered for the definition of the reference transport profile.

Transport mode	**Number of trips (trips/person/day)**	**Transport distances (km/person/day)**
Car	1.90	31.17
Bus	0.05	0.84
Tram/metro	0.02	0.15
Train	0.05	1.92
Bicycle	0.31	1.25
Electric bicycle	0.02	0.18
On foot	0.31	0.55
Moped	0.01	0.04
Motorcycle	0.00	0.06
Coach	0.03	0.95
Other	0.03	9.02
No answer	0.01	0.00
Total	**2.74**	**46.13**
Total (excluding 5 last categories)	**2.67**	**36.06**

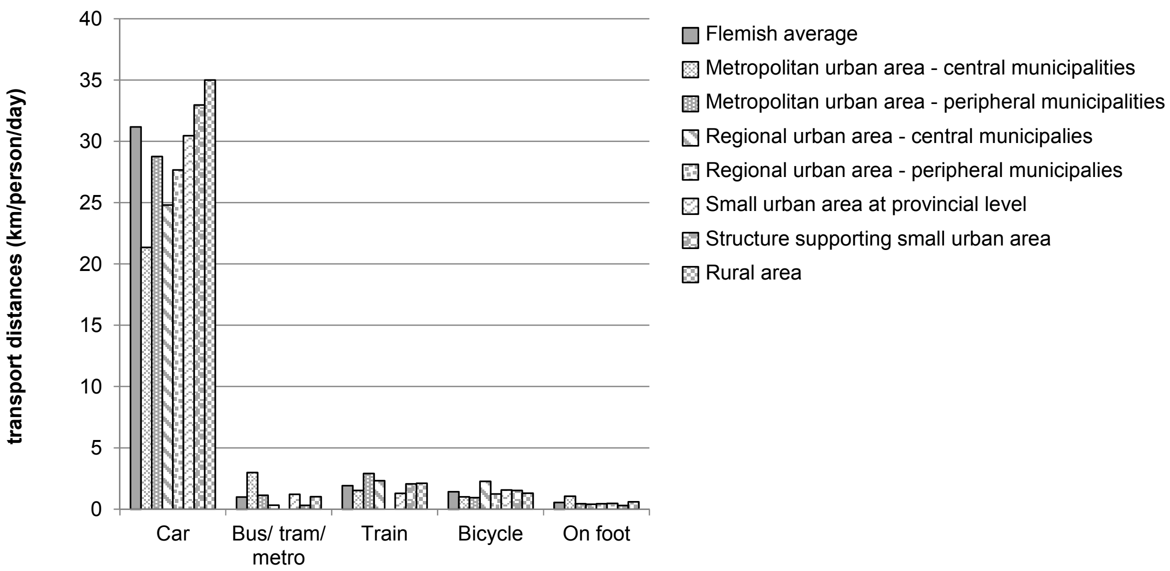

Figure 5.12: Daily transport distances per person for the different areas of the Structure Plan Flanders, based on (Declercq et al. 2016)[25].

[25] The category “Urban area around Brussels” is not included in the graph as data are missing for public transport and bicycle use.

Besides data on average transport distances, the reference transport profile should also include data on the type of fuel used by the different transport modes. This is necessary for the financial and environmental impact assessment per transport mode. Based on Belgian statistics for the year 2015 (Belgian Federal Government 2017c), a share of 62% diesel cars and 38% petrol cars is considered. Natural gas and electric cars are not included in the reference transport profile as their share doesn't exceed 0.5%. However, an alternative scenario including the full electrification of the Belgian car fleet is analysed in Chapter 8. Concerning public transport, diesel is assumed as main fuel for buses and electricity for trams, metro and trains.

5.4.2 Site specific transport profile

The site specific transport profile is calculated by multiplying the reference transport distances with corrections factors, taking into account the characteristics of the built environment and their impact on the transport behaviour. This approach was already implemented in two transport assessment methods focussing on the Swiss and Dutch context respectively. First, the method developed by the Swiss Society of Engineers and Architects (SIA) proposes correction factors to be applied on the average energy consumption and greenhouse gas emissions for car transport in Switzerland (SIA 2011). Based on statistical data, correction factors are defined for six parameters which are selected for their major influence on user transport: the neighbourhood location, access to public transport, distance to a supermarket, availability of parking spaces, car availability and availability of public transport subscription. The SIA method was applied at the neighbourhood scale level in the Swiss context to compare various densification scenarios and their impact on user transport (Riera Pérez and Rey 2013).

Second, the method developed by the Dutch consultancy company MuConsult includes correction terms for the number of transport trips and transport distances per transport mode (MuConsult B.V 2009). These correction terms consist of regression coefficients which are calculated based on a multivariate regression analysis applied on the results of a transport survey carried out in the Netherlands. Regression coefficients are available for the following characteristics of the built environment: dwelling characteristics (e.g. typology, availability of a garden and availability of a garage), street characteristics (e.g. link to bicycle network, availability of parking facilities and distance to public transport) and neighbourhood characteristics (e.g. availability of green areas, pedestrian friendliness and access to shops). The MuConsult method was implemented for the calculation of the impact of user transport in the LCA-tool GreenCalc+ (Stichting Sureac 2013).

Due to the lack of a specific method for the Belgian context, the MuConsult method is selected as the most appropriate for this research[26], as it allows to consider the influence of a wide set of characteristics of the built environment. Furthermore, the impact on the different transport

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[26] The representativeness of the Dutch MuConsult method for the Belgian context should be further investigated as differences in transport behaviour are expected between both countries. Therefore the development of a specific method for the Belgian context is highly recommended.

modes can be analysed as regression coefficients are available for transport by car, bicycle, foot and public transport. In the SIA method, potential shifts in transport modes cannot be modelled as correction factors are only available for car transport.

To apply the MuConsult method in this research, the regression coefficients for the number of trips[27] have been converted to relative values, expressed as a percentage of the average number of trips. This conversion consists of two steps which are illustrated in Table 5.6, based on the regression coefficients for car transport for the characteristic “Slow traffic residential zone”. In a first step, the original regression coefficients are rescaled compared to the average. For characteristics of the built environment which can take *n* possible values, the rescaled regression coefficients are calculated based on Formula [5.18]:

$$R_x^{'} = R_x - \sum_{i=1}^{n} f_i R_i \qquad [5.18]$$

With:

- $R_x^{'}$ = rescaled regression coefficient for value *x*
- R_x = original regression coefficient for value *x*
- f_i = frequency of occurrence of value *i* in the average situation, as reported in the MU Consult study[28]
- R_i = original regression coefficient for value *i*

In a second step, the rescaled regression coefficients are translated to percentages of the average number of trips based on Formula [5.19]:

$$P_x^{'} = \frac{R_x^{'}}{T_{mean}} \qquad [5.19]$$

With:

- $P_x^{'}$ = rescaled regression coefficient for value *x*, expressed as a percentage of the average number of trips
- T_{mean} = average number of trips, as reported in the MU Consult study

Table 5.6: Calculation of the rescaled regression coefficients for car transport for the characteristic “Slow traffic residential zone”.

Characteristic	***i***	***x***	***R***	***f***	***R’***	T_{mean}	***P’***
Slow traffic residential zone	1	Yes	-0.98	13%	-0.85	4.78	**-18%**
	2	No	0	87%	0.13	4.78	**+3%**

[27] The regression coefficients for the transport distances show a number of inconsistencies and are therefore not used in this research.

[28] When the frequency of occurrence is not reported, an equal distribution between the possible values is assumed.

These percentages can then be used as correction terms on the reference transport profile for Flanders. The adapted regression coefficients are reported in Table 5.7. Characteristics of the built environment with a significant impact (more than 10% increase or decrease) are indicated in grey. As an example, the following characteristics have a significant impact on car transport: the building typology, availability of a garden, availability of a garage/storage, location in a slow traffic residential zone and accessibility of shops (other than food shopping). Concerning public transport, the impact of some characteristics can be really high. However it should be mentioned that there were few public transport users among the respondents to the MuConsult survey. The results related to public transport should therefore be interpreted with caution.

Table 5.7: Adapted regression coefficients for the number of trips (expressed as a percentage of the average), based on (MuConsult B.V 2009). The percentage increases or decreases higher than 10% are indicated in grey.

Characteristics		**Car**	**Bicycle**	**On foot**	**Public transport**
		(4.78)*	**(3.26)***	**(2.09)***	**(0.47)***
Dwelling characteristics					
Typology	Detached	+6%	-17%	-8%	-27%
	Semi-detached	+13%	+14%	-6%	-17%
	Terraced	-4%	-1%	+10%	+26%
	Apartment	-4%	+3%	-14%	-27%
Garden	With privacy	-14%	+4%	-2%	-14%
	Without privacy	+8%	+8%	-6%	-29%
	No garden	+4%	-25%	+16%	+90%
Garage/ storage	Yes	+1%	-0.4%	-1%	-6%
	No	-24%	+8%	+19%	+141%
Unpleasant view	Yes	-3%	+5%	+7%	+22%
	No	+3%	-5%	-7%	-22%
Street characteristics					
Link to bicycle network	Yes	-8%	+10%	-10%	-5%
	No	+8%	-10%	+10%	+5%
Good parking facilities	Yes	+1%	+0.3%	-3%	-7%
	No	-4%	-2%	+20%	+51%
Distance to public transport	stop < 300 m	-8%	-4%	+7%	+4%
	stop > 300 m	+1%	+1%	-1%	-1%
Slow traffic residential zone	Yes	-18%	+18%	+2%	+44%
	No	+3%	-3%	-0.3%	-7%
30 km zone	Yes	+1%	-8%	+7%	+60%
	No	-0.1%	+1%	-1%	-10%
Traffic calming measures	Yes	-3%	+6%	-0.3%	+13%
	No	+2%	-4%	+0.2%	-8%

Characteristics		Car (4.78)*	Bicycle (3.26)*	On foot (2.09)*	Public transport (0.47)*
Neighbourhood characteristics					
Addresses per hectare**	< 20 /ha	-0.3%	+1%	-0.1%	-1%
	> 20 /ha	+0.3%	-1%	+0.1%	+1%
Green areas	Yes	+3%	-5%	-6%	+21%
	No	-3%	+5%	+6%	-21%
Pedestrian friendliness	Yes	+1%	-15%	+13%	-7%
	No	-0.4%	+7%	-6%	+3%
Cycle friendliness	Yes	-1%	+9%	-3%	-13%
	No	+1%	-4%	+2%	+6%
Time to main road	< 1min	+2%	-2%	-0.2%	-5%
	> 1min	-5%	+7%	+1%	+14%
Accessibility daily food shopping	Good	+1%	+14%	+22%	-4%
	Bad	-2%	-33%	-51%	+10%
Accessibility weekly food shopping	Good	-1%	-5%	+2%	+28%
	Bad	+2%	+10%	-4%	-59%
Accessibility other shops	Good	+10%	+3%	-15%	+8%
	Bad	-11%	-3%	+16%	-9%

* Average number of back-and-forth trips per person per week for the participants in the MuConsult survey (MuConsult B.V 2009).

**The regression coefficients have to be multiplied with the number of addresses per hectare.

The calculation of the site specific transport profile is illustrated in Table 5.8, based on a fictive example including three street characteristics, stimulating the use of alternative transport modes. The total correction term to be applied to the reference transport profile is calculated as the sum of the correction terms of the considered characteristics. The resulting site specific transport profile shows a decrease in the use of the car (-33%) in favour of the bicycle (+23%) and public transport (+43%).

Table 5.8: Calculation of the site specific transport profile, illustrated based on a fictive example including three street characteristics.

	Car	Bicycle	On foot	Public transport
Reference transport profile Flanders (km/person/day)	31.17	1.42	0.55	2.92
Good link to bicycle network	-8%	+10%	-10%	-5%
Distance to public transport < 300m	-8%	-4%	+7%	+4%
Slow traffic residential zone	-18%	+18%	+2%	+44%
Total correction terms	**-33%**	**+23%**	**-1%**	**+43%**
Site specific transport profile (km/person/day)	**20.76**	**1.75**	**0.54**	**4.16**

5.4.3 Impact of user transport

Based on the site specific transport profile, the environmental and financial impact of user transport per inhabitant can be calculated by multiplying the corrected transport distances with the environmental and financial impact per transport mode. The environmental and financial data used in this research are described in the subsequent paragraphs.

Environmental impact of transport modes

The environmental impact per transport mode, expressed in euro per person-kilometre (pkm), is shown in Figure 5.13. The data are based on the transport records from the Ecoinvent version 2.2 database (Frischknecht et al. 2007; Spielmann et al. 2007), which include the fuel consumption and the life cycle of the vehicle and required road or rail infrastructure. In this research, the records are adapted to the Belgian context by using the Belgian electricity mix and average vehicle occupancy rates in Flanders (indicated in Figure 5.13).

Significant differences in environmental impact are noticed between the transport modes (Figure 5.13). Compared to a diesel car, the environmental impact of public transport is about 50% lower for the bus and 70% lower for the train and tram. The lowest environmental impact is obtained for bicycle transport, of which the impact is about 90% lower, compared to a diesel car. Concerning the use of electric vehicles, the transport impact for an electric car is 18% lower, compared to a diesel car. The reason for this relatively limited decrease is that the impact reduction from the fuel is partially compensated by a higher impact of the vehicle resulting from the heavy car batteries.

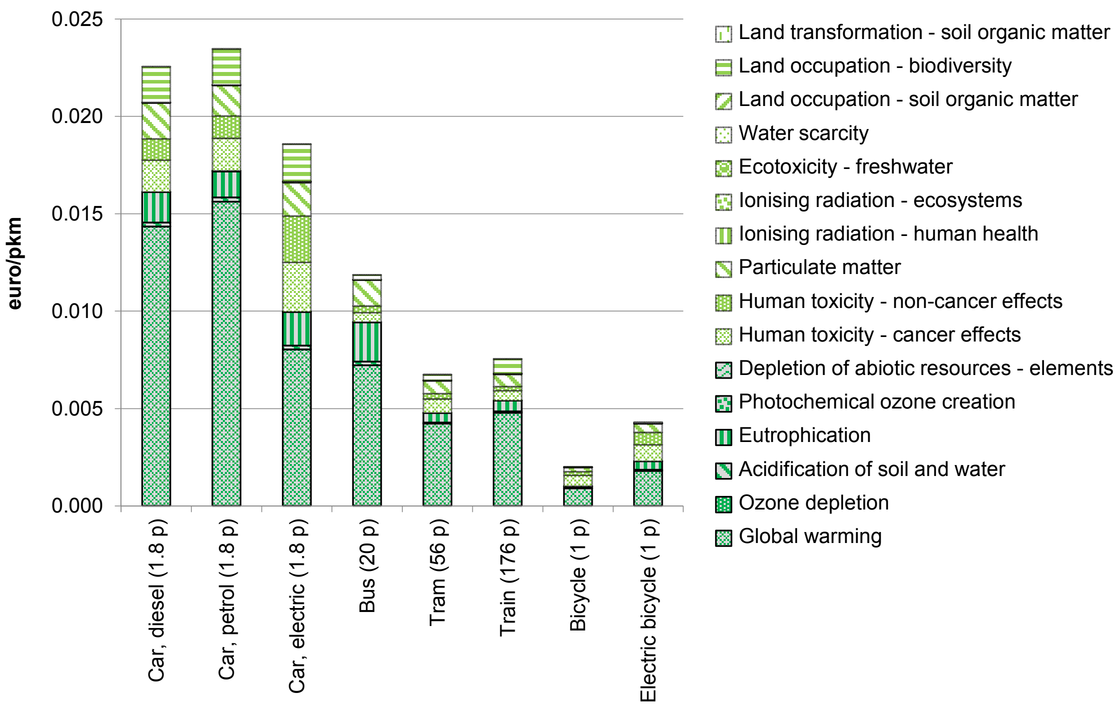

Figure 5.13: Environmental cost of transport modes. The average occupancy rate of each transport mode (number of people per vehicle) is indicated between brackets.

Financial impact of transport modes

The financial cost per transport mode, expressed in euro per pkm, is shown in Figure 5.14. The data are based on a study of Transport & Mobility Leuven (TML), including the calculation of consumer prices for various transport modes (Delhaye et al. 2010; Delhaye et al. 2017). For private transport, the consumer prices cover the investment cost, maintenance cost, fuel cost, insurance cost, taxes and subsidies. For public transport, the consumer prices are calculated based on the revenues from the ticket sales. Compared to the original TML study, parameters - such as the lifetime kilometric performance[29] and vehicle fuel consumption - have been adapted to be in line with the assumptions made for the calculation of the environmental impact based on the Ecoinvent data (Spielmann et al. 2007).

As for the environmental impact, significant differences in financial cost are noticed between the transport modes (Figure 5.14). Compared to a diesel car, the financial cost of public transport is about 90% lower for the bus and tram and 70% for the train. The reason is that public transport is highly subsidised in Belgium. Subsidies equal about 435% and 95% of the revenues from the ticket sales for the bus/tram and train respectively. Concerning bicycle transport, the investment and maintenance costs are amortized over a limited number of kilometres[30]. As a result, the transport cost is only about 65% lower compared to a diesel car. Finally, the transport financial cost for electric vehicles is quite high due to the high investment cost. Compared to a diesel car, the transport cost for an electric car is about 25% higher while the transport cost for an electric bicycle is only 15% lower.

Regarding the growth rate of the transport cost, an average real growth rate of 0.3% is calculated based on the price evolution per transport mode between 2000 and 2008, such as reported in the TML study (Delhaye et al. 2010).

[29] Total number of kilometres travelled during the life span of the vehicle.

[30] A lifetime kilometric performance of 15,000km is considered for a bicycle, compared to 150,000km for a car (Spielmann et al. 2007).

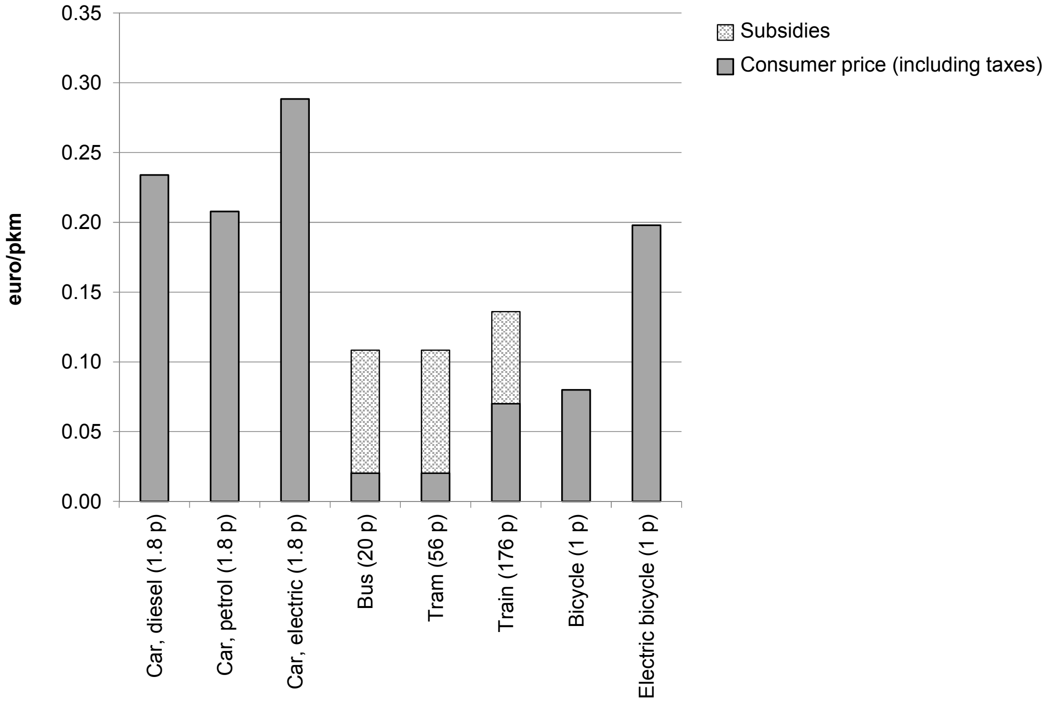

Figure 5.14: Financial cost of transport modes in Flanders in 2015, based on (Delhaye et al. 2010; Delhaye et al. 2017). The average occupancy rate per transport mode is indicated between brackets.

5.5 Neighbourhood qualities

A comprehensive framework is developed for the assessment of qualities in neighbourhoods. The quality aspects included in this framework are based on a literature review of existing scoring tools for neighbourhoods. In the subsequent sections, the results of the literature review are presented and the derived framework is described.

5.5.1 Assessment of neighbourhood qualities in scoring tools

The scoring tools for neighbourhoods analysed in Chapter 2 are selected for the literature review: BREEAM Communities (BRE 2016), CASBEE for Urban Development (IBEC and JSBC 2014), DZM Wijken (Flemish Government 2017d), DGNB New Urban Districts (DGNB GmbH 2012) and Strategies Sustainable Building Flanders (Vandevyvere 2010). The neighbourhood qualities assessed in those tools have been highlighted and classified in a number of quality aspects (Table 5.9). A distinction is made between five main categories: functional qualities, technical qualities, site qualities, socio-cultural qualities and process qualities.

The analysis shows that scoring tools for neighbourhoods especially focus on site qualities, socio-cultural qualities and process qualities, which are particularly relevant at the community scale level. Less attention is paid to functional and technical qualities which are extensively evaluated in tools at the building level. Depending on the tool, some quality aspects are assessed in more detail. For example, many assessment issues in the DZM Wijken are related to process qualities. Another example is the assessment of local impacts, which is more elaborated in BREEAM Communities and DZM Wijken.

Table 5.9: Qualities assessed in scoring tools for neighbourhoods. For each quality aspect the related assessment issues are mentioned based on their code, as defined in the various scoring tools (see Appendix A).

Quality aspects	BREEAM Communities	CASBEE for Urban Development	DZM Wijken	DGNB New Urban Districts	Strategies Sustainable Building Flanders
Functional qualities					
Accessibility and spatial relations	SE 15		W&W 02.01	SOC3.2	
Flexibility, adaptability		Q 3.3.2	MAT 03.01	SOC3.3	E4
Technical qualities					
Indoor comfort[31]	SE 04				
Provision of utilities	SE 09	Q 3.3.2, Q 3.3.1		TEC1.1, TEC1.2, TEC1.4	
Safety and security		Q 2.2.2			S1
Crime prevention		Q 2.2.3		SOC2.1	S1
Fire prevention		Q 2.2.1			
Site qualities					
Accessibility and centrality			MOB 01.01	SOC3.2	M4
Services and facilities	SE 02, SE 06	Q 2.3.1	W&W 01.01	SOC1.2, SOC3.1	S2
Transport infrastructure	SE 12, TM 02, TM 03, TM 05, TM 06	Q 2.2.2, Q 3.1.1	MOB 02.01, MOB 02.02, MOB 02.03	TEC3.1, TEC3.2, TEC3.3, TEC3.4, TEC3.5	M5, S1
Green and water infrastructure	SE 11, LE 04	Q 1.2.1	GRN 01.01, GRN 02.01	ENV1.4	M3, M4
Reduction of nuisances and local impacts	SE 03, SE 04, SE 08, SE 10, SE 13, SE 16, LE 03	Q 2.1.1, Q 2.2.1	FYS 01.02, FYS 02.01, FYS 02.03, FYS 02.04, FYS 02.05, FYS 02.06, FYS 02.07, WAT 01.01, WAT 01.02	ENV1.2, ENV1.3, ENV1.5, SOC2.3	M6

[31] Indoor comfort is mostly evaluated at the building level as it highly depends on the technical choices in buildings.

Quality aspects	BREEAM Communities	CASBEE for Urban Development	DZM Wijken	DGNB New Urban Districts	Strategies Sustainable Building Flanders
Socio-cultural qualities					
Diversity	SE 02, SE06	Q 2.3.1	W&W 01.01, W&W 01.02	SOC1.1, SOC1.2	S2, S3
Inclusivity	SE 05, SE 15	Q 2.3.1	W&W 02.01, W&W 02.02	SOC1.1, SOC1.2, SOC3.2	S2, S3
Sociability[32]	SE 07		W&W 01.01	SOC1.1, SOC2.2	S4
Identity and cultural value	SE 14, LE 05	Q 2.3.2	MAT 01.02	SOC4.3	R2
Spatial and architectural quality	GO 03, LE 05	Q 2.3.2, Q 3.1.2	KWA 02.01	SOC4.1, SOC4.2, SOC4.4	R1
Social entrepreneurship			KWA 03.03		
Local economy	SE 01, SE17	Q 3.2.2	W&W 03.01	ECO1.2, SOC1.1	E2
Process qualities					
Design, construction and use	GO 03, GO 04	Q 2.1.1	KWA 01.01, KWA 01.02, KWA 02.02, KWA 04.01, KWA 04.02, KWA 04.03, W&W 04.02, MOB 03.01, GRN 03.01, WAT 03.01, WAT 03.02, MAT 03.02	PRO2.1, PRO2.2, PRO2.3, PRO3.1, PRO3.2, PRO3.3, PRO3.4	I1, I3, M6
Participation	GO 01, GO 02	Q 2.1.2	KWA 03.01, KWA 03.02	PRO1.1	I2
Long term vision	SE 10	Q 3.3.2	KWA 01.03, W&W 04.01, MOB 03.02, FYS 03.01, GRN 03.02, WAT 04.01, WAT 04.02, ENE B.02.01, ENE B.02.02	SOC3.3	S5, E4

[32] Sociability refers to design measures encouraging social interactions, such as the provision of collective and multiple use spaces.

5.5.2 Comprehensive assessment framework for neighbourhood qualities

Based on the literature review, a comprehensive framework is developed for the assessment of neighbourhood qualities (Figure 5.15). Besides the subdivision in five main categories (functional, technical, site, socio-cultural and process qualities), a distinction is made between three quality clusters. The first cluster "User qualities" includes qualities which are relevant for the neighbourhood user or inhabitant. Those qualities are important from an individual point of view. Functional and technical qualities can be considered as part of this cluster.

The second cluster "Community related qualities" includes qualities relevant for the society and local community. Socio-cultural qualities belong to this category. "Community related qualities" can be imposed via regulations or stimulated via subsidies. For example, regulations can be introduced concerning the conservation of historical buildings or the accessibility of buildings for disabled people. Another example are subsidies for the provision of affordable housing. The distinction between "User qualities" and "Community related qualities" is however not strictly delimited as some qualities, such as site qualities, can fall in both clusters. For example, the provision of public green spaces is a quality which is relevant for both the neighbourhood users and the people living in the surroundings (local community).

Finally, the third cluster focuses on the process and governance. A well-structured and well-organized process is essential to deal with the complexity of neighbourhood development projects. Compared to "User qualities" and "Community related qualities", the process qualities should not be considered as an objective but rather as a means to achieve the sustainability goals.

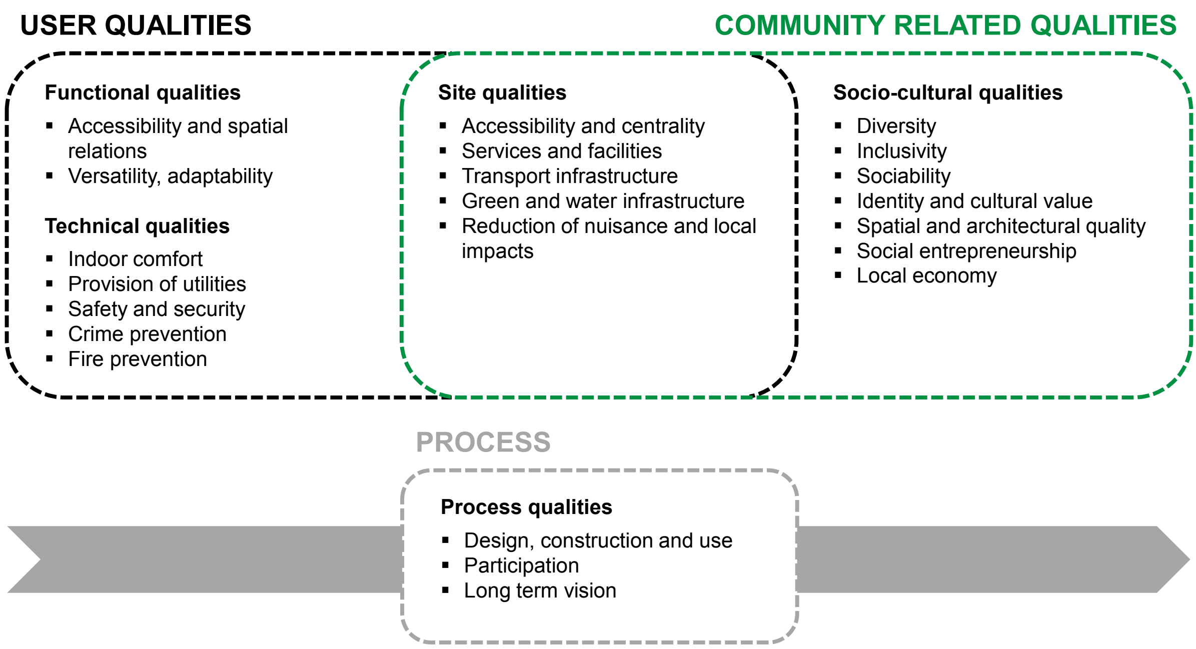

Figure 5.15: Framework for the assessment of neighbourhood qualities.

In the subsequent paragraphs, the quality aspects included in each of the five main categories are described. The framework is only elaborated conceptually, without the attribution of quality cores and weighting to the various quality aspects. As quality weighting is highly subjective, the assessment of qualities in a real project should be the task of an expert panel including various stakeholders and a wide range of user profiles. In this research, a detailed quality assessment of the analysed schematic neighbourhood models is not included but the impact on qualities of the various sustainability measures analysed is systematically mentioned (see Chapter 9).

Functional qualities

This category focuses on the assessment of functional characteristics at the neighbourhood scale level. The following sub-aspects are assessed:

1. Accessibility and spatial relations: accessibility of buildings and open spaces, implementation of a legible and logical circulation system.
2. Versatility, adaptability: design of adaptable, transformable and multi-functional building layouts, infrastructure and open spaces. This sub-aspect focuses on the “Design for Change” strategy (Debacker et al. 2015) and how the neighbourhood design can be adapted to changing needs, such as changes in household needs and performance standards. This sub-aspect is closely related to the long term vision on the neighbourhood development (see “Process qualities).

Technical qualities

The technical choices and characteristics are assessed in this category. Five sub-aspects are evaluated:

1. Indoor comfort: thermal, acoustical and visual comfort, indoor air quality. Indoor comfort is mostly evaluated at the building level as it highly depends on the technical choices in buildings. Indoor comfort can however also be influenced by decisions at the neighbourhood level and site characteristics (see “Site qualities”). For example, noise pollution can have a high impact on the acoustical comfort in buildings.
2. Provision of utilities: availability of gas, district heating, electricity, water, sewerage and telecommunication networks.
3. Safety and security: physical safety (including fall risk prevention and traffic safety).
4. Crime prevention: prevention of criminality and vandalism, such as measures to improve social control, surveillance cameras and an adapted lighting concept.
5. Fire prevention: measures to improve the fire safety, such as the design of evacuation routes, integration of fire breaks and the fire resistance of the building materials used.

Site qualities

This category focuses on the qualities of the location and the surroundings. The following five sub-aspects are assessed:

1. Accessibility and centrality: accessibility of the location and proximity of daily destinations.
2. Services and facilities: availability of various services and facilities in the neighbourhood such as shops, restaurants and pubs, leisure facilities (sport, culture), educational facilities, facilities for health and social care.
3. Transport infrastructure: infrastructure and facilities for various transport modes, including pedestrians, bicycles, public transport and cars.
4. Green and water infrastructure: provision of recreational green areas and integration of water in the public space.
5. Reduction of nuisances and local impacts: impacts related to local pollution (air, soil, water), noise pollution, odour, electromagnetic radiation, wind effects, urban heat island, daylight access to buildings and solar access to open spaces, visual and light pollution, flood management… Many of these aspects are related to environmental issues. However, as current E-LCA methods only cover regional and global impacts, local impacts are evaluated in this research as part of the quality assessment.

Socio-cultural qualities

As mentioned in Chapter 3, the social performance of the neighbourhood is evaluated as part of the quality assessment. Social aspects are bundled in the category “Socio-cultural qualities”, covering seven sub-aspects:

1. Diversity: stimulation of social mix by including a mix of housing types, facilities and types of open spaces.
2. Inclusivity: universal design promoting the inclusion of all users such as various age groups, disabled people, other beliefs and ethnicities.
3. Sociability: design encouraging social interactions such as the provision of collective and multiple use spaces.
4. Identity and cultural value: consideration of the architectural identity (e.g. preservation of historical buildings, respect for the existing building context and use of local building materials) and landscape identity (e.g. plantation of native species, preservation of landscape features and landmarks).
5. Spatial and architectural quality: design quality related to the outside characteristics of the buildings, open spaces and landscape.
6. Social entrepreneurship: social responsibility of contractors and working conditions on the building site.[33]

[33] Many aspects related to social entrepreneurship are already integrated in Belgian regulations and therefore applicable to products and services provided in Belgium.

7. Local economy: enhancement of the local economic activity. This sub-aspect is often evaluated as an economic issue in scoring tools. In this research, it is considered as a socio-cultural quality as local economy contributes to the social wellbeing in the neighbourhood.[34]

Process qualities

This category focuses on the qualities of the process. As already mentioned, process qualities should not be considered as an objective but rather as a means to achieve the sustainability goals. Therefore it is recommended to assess these qualities separately and not to include them in the calculation of a quality score. The category “Process qualities” covers three sub-aspects:

1. Design, construction and use: assessment of the process related to the design, construction and use of the neighbourhood. This includes issues such as concept finding, planning, quality control, limitation of nuisance during the construction works, maintenance and management.
2. Participation: participation and consultation of stakeholders and users.
3. Long term vision: development of a vision on future changes, such as climate change, population and social changes, functional and technical changes.

5.6 Conclusions

In this chapter, the scope of the original SuFiQuaD sustainability assessment method is extended with an adapted assessment of operational energy use for the urban planning phase (based on the EHDD method with a more accurate calculation of solar gains), a refined assessment of operational water use, and an additional assessment of primary land use, user transport and neighbourhood qualities. For the first four aspects, quantitative assessment methods are used and integrated in the life cycle approach. The use of the same life cycle methodology to assess various aspects allows to analyse and compare their contribution to the life cycle impact of neighbourhoods (see Chapter 8).

Concerning the assessment of neighbourhood qualities, a qualitative approach is selected, which is defined distinctively but should be used in addition to the quantitative life cycle methodology. The approach consists of a comprehensive framework covering the various quality aspects which are relevant at the neighbourhood scale level. The framework does not include detailed quality criteria and scores but is rather a global guidance for urban designers and stakeholders in order to reflect on neighbourhood qualities and their integration in neighbourhood development projects.

[34] The enhancement of the local economy should not lead to protectionism, reducing the growth possibilities for third parties.

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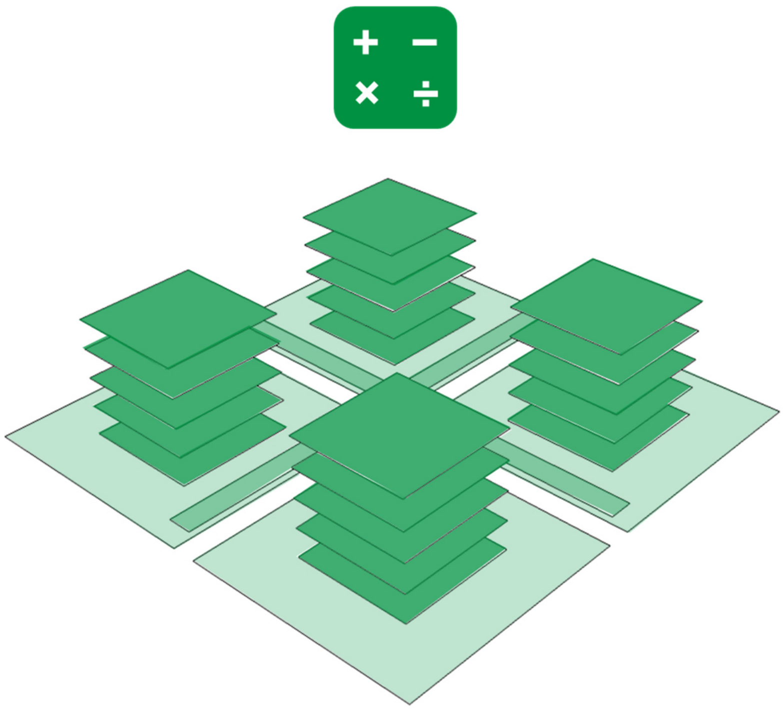
CHAPTER 6

Calculation model

In this chapter the calculation model to assess the financial and environmental impact of neighbourhoods is presented. The calculation model is based on the existing model developed for the MMG research project ("Environmental profile of building elements") and the ongoing research to develop a Belgian tool for the assessment of the environmental impact of buildings (Allacker et al. 2013; Trigaux et al. 2013). In the first section, the existing building calculation model is described. The second section focuses on the extension of the calculation model to assess the impact of neighbourhoods.



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6.1 Building calculation model

The structure of the calculation model is illustrated in Figure 6.1. The calculation model is implemented in a number of Excel spreadsheets, which in turn are composed of different worksheets. In the existing building calculation model a distinction is made between five categories of worksheets: “General parameters”, “Databases”, “Scenarios”, “Composed objects” and “Visualisations”. For those categories, the main worksheets[1] are described in the subsequent subsections with a specific focus on the refinements which have been implemented in this research.

6.1.1 “General parameters” worksheet

The general parameters, which are used for the calculations in the various worksheets, are grouped in the “GenPar” worksheet. Parameters included are the monetary values per impact category (for the environmental cost calculations), the percentage of material losses on the construction site, parameters for the calculation of the operational energy use at the building element level (Equivalent Heating Degree Days and efficiency of the heating installation), parameters related to the building life span (year of construction and demolition) and economic parameters (growth, discount and VAT rates).

6.1.2 “Databases” worksheets

Databases for energy and water sources, transport and EOL

The environmental impact data for energy and water sources, transport modes (used for the transportation of building materials and waste) and EOL processes are listed in three databases: worksheets “DB_EcoInEW”, “DB_EcoInTransp”, and “DB_EcoInEOL” respectively. For each product or process, the databases consist of the environmental impacts (characterised values) calculated with the SimaPro software (PRé Consultants 2017), based on the LCI datasets from Ecoinvent version 2.2 (Frischknecht et al. 2007).

[1]Beside the main worksheets including the parameters and calculations, supporting worksheets are used for linking the data between the various spreadsheets. These supporting worksheets are not discussed in this chapter.

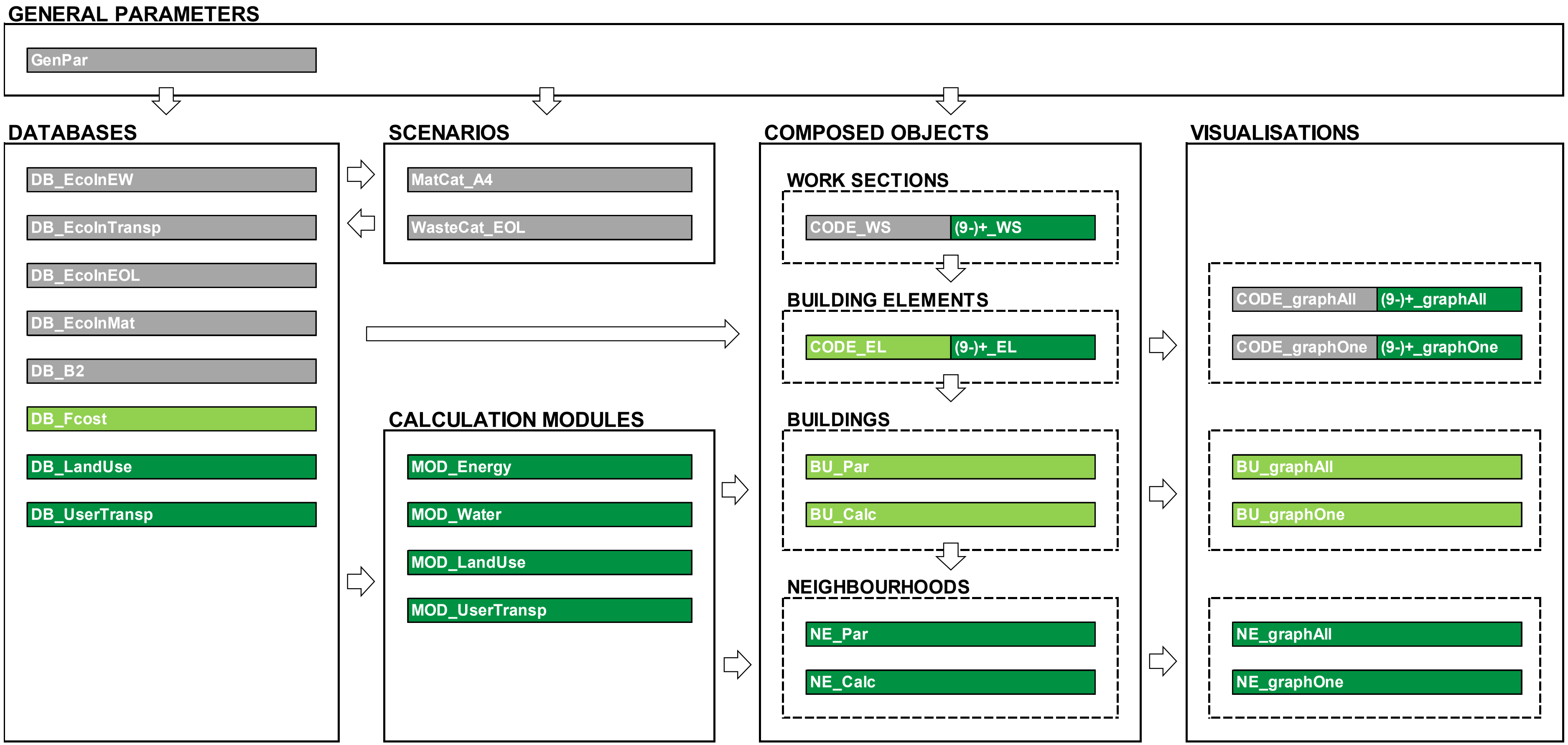

Figure 6.1: Structure of the calculation model and main worksheets. The worksheets of the existing building calculation model, which have been refined in this research, are indicated in light green. The additional worksheets to assess the impact of neighbourhoods are indicated in dark green.

Database materials

The database of materials (worksheet "DB_EcoInMat") is the central database containing the environmental impact data of the building materials, which are used for the composition of the work sections. First, the database includes the environmental impacts for the production of building materials (module A1-A3), calculated in SimaPro based on Ecoinvent datasets. Second, for each building material, scenarios for the transport to the construction site, waste transport and EOL processes are selected. The scenarios are defined in specific worksheets (see Section 6.1.3). Based on the selection, the environmental impacts are calculated for the following life cycle modules: transport to the site (module A4), waste transport (module C2), waste processing (module C3) and waste disposal (module C4).

Database maintenance processes

The database of maintenance processes (worksheet "DB_B2") includes the calculation of the environmental impacts related to cleaning, small and big maintenance activities (module B2). To calculate the environmental impacts, the maintenance processes are divided into sub-processes. For example, floor cleaning is subdivided into the use of tap water and an all-purpose cleaner. For each sub-process, a material or process from the material database (worksheet "DB_EcoInMat") is selected and input data on the material or process ratios are entered. The environmental impacts of each maintenance process can then be calculated as the sum of the impacts of all sub-processes.

Database financial costs

The database of financial costs (worksheet "DB_FCosts") is the central database containing the financial costs of the various work sections, including data related to new construction and refurbishment (module A1 up to A5), maintenance (module B2) and demolition (module C1). Different data sources are used, including the ASPEN and SPON'S price books and product specific data (ASPEN 2015a; Spon press 2015a; ASPEN 2015b; Spon press 2015b). The source of the cost for each work section is mentioned in the worksheet.

6.1.3 "Scenarios" worksheets

The scenarios related to the transport to the construction site (module A4) and the EOL stage (module C1 up to C4), which are reported in (Allacker et al. 2013)[2], are included in the worksheets "MatCat_A4" and "WasteCat_EOL" respectively. Concerning the transport to the construction site, transportation scenarios are defined for a number of material categories. These scenarios include parameters related the distribution over the transport routes, transport modes and transport distances.

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[2] The scenarios should be updated in future to be in line with the recently published Belgian Product Category Rules for buildings (NBN 2017).

Concerning the EOL stage, scenarios are described for a number of waste categories. Per waste category, the following parameters are defined: type of sorting process, distribution over the type of EOL treatments (i.e. landfilling, incineration, reuse, and/or recycling) and parameters related to waste transport (i.e. transport routes, transport modes and transport distances).

6.1.4 "Composed objects" worksheets

The "Composed objects" worksheets consist of the environmental and financial impact calculation of the objects at the various scale levels. In accordance with the principle of the element method, each object at a specific scale level is composed of objects from the lower scale levels. In the building calculation model a distinction is made between the following scale levels and related worksheets: "Work sections", "Building elements" and "Buildings".

"Work sections" worksheets

The environmental impact of the work sections are calculated in the worksheets "CODE_WS", where the code refers to the type of macro-element in which the work sections are used. For example, the worksheet "(21)+_WS" consists of the work sections used for the composition of external walls. To calculate the environmental impact, the work sections are divided into constituting building materials or processes. For each building material/process, a material/process is selected from the databases and input data on the material/process ratios are entered. The environmental impacts of each work section are then calculated as the sum of the impacts of all constituting building materials/processes. For the financial costs calculations, this subdivision in buildings materials/processes is not necessary as cost data are directly available at the level of the work sections (see "Database financial costs").

Besides the constituting building materials, maintenance processes (worksheet "DB_B2"), demolition processes (worksheet "DB_EcoInEOL") and thermal characteristics (used for the calculation of the thermal resistance), are attributed to each work section. As a result, the environmental impact of the work sections is calculated for the following life cycle modules: production (module A1-A3), transport to site (module A4), construction and installation (module A5), one year of cleaning (module B2.1), one small and big maintenance (module B2.2 and B2.3), one replacement (module B4), deconstruction/demolition (module C1), waste transport (module C2), waste processing (module C3) and waste disposal (module C4).

"Building elements" worksheets

The environmental and financial impacts of the building elements are calculated in the worksheets "CODE_EL", where the code refers to the type of macro-element. For each building element, the constituting work sections, corresponding ratios and life cycle scenarios (i.e. maintenance and replacement frequencies, scenarios for refurbishments…) are defined. In this research the modelling of the life cycle scenarios has been refined. This is described in detail in Appendix B.

Based on the life cycle scenarios, the financial and environmental impacts of the constituting work sections are calculated over the whole building life cycle, including the following life cycle modules: pre-construction (module A0), production (module A1-A3), transport to site (module A4), construction (module A5), maintenance (module B2), replacement (module B4), refurbishment (module B5), deconstruction/demolition (module C1), waste transport (module C2), waste processing (module C3) and waste disposal (module C4). The financial and environmental impacts of each building element is then calculated as the sum of the impacts of all constituting work sections.

Furthermore, the U-value of each building element is calculated based on the thermal characteristics of the constituting work sections and the thermal resistance of the inside and outside surface. The U-value is used for the calculation of the impact of the energy use resulting from transmission losses (module B6), based on the static Equivalent Heating Degree Days (EHDD) method (DPWB 1984a; DPWB 1984b)[3].

"Buildings" worksheets

The "Buildings" worksheets consist of two worksheets: "BU_Par" and "BU_Calc". The first worksheet contains the input parameters of the analysed buildings. Parameters related to the building geometry, the constituting building elements and the calculation of the operational energy use[4] and water use[5] have to be defined. These parameters can be grouped in variants to allow for an easy selection and combination of pre-defined input data. Concerning the building geometry, the input data can be entered in a detailed or simplified way. In the simplified approach, only the global shape and geometry is defined while the amount of the various building elements is automatically calculated based on default values and geometric relationships (see Appendix C for a detailed description). This approach is particularly appropriate for the master planning phase of neighbourhoods, when only the general layout and building geometry are defined.

In the second worksheet "BU_Calc" the environmental and financial impacts of the buildings are calculated. The input parameters are automatically collected from the worksheet "BU_Par". Based on the input parameters and the building element impact data from the worksheets "CODE_EL", the financial and environmental impacts of the constituting building

[3] A default value of 1200 EHDD is assumed for the calculations at the building element level (Allacker et al. 2013). At the building level, the impact of the internal gains and solar gains is estimated more accurately based on the dynamic EHDD method (see Chapter 5).

[4] Various parameters are required for the calculation of the energy use for heating, domestic hot water ventilation and lighting and appliances (see Chapter 5). Parameters included are the net energy demand for heating (calculated based on the dynamic EHDD method) and domestic hot water, electricity consumption for lighting and appliances and characteristics of the technical installation (e.g. efficiency values, ventilator power and installed PV system).

[5] Parameters included are the tap water consumption and the volume of wastewater and rainwater discharge to the sanitary sewer. These parameters are calculated based on the water calculation method developed by the Belgian Building Research Institute (BBRI) and described in Chapter 5.

elements are calculated for the various life cycle modules (from module A up to module C). The financial and environmental impacts of the buildings are consequently calculated as the sum of all constituting building elements. Concerning the operational energy and water use (module B6 and B7), the impacts are calculated for the whole building in separate calculation modules (see Section 6.2.2).

6.1.5 “Visualisations” worksheets

The “Visualisations” worksheets graphically visualise the results of the financial and environmental impact calculations. Visualisations are available for various scale levels including the building elements and buildings. For a user friendly interpretation of the results, the same graphical conventions are used at the various scale levels.

For each type of building element, the visualisations are subdivided in two worksheets: one for the comparison of all variants of that building element (worksheets “CODE_graphAll”) and one for the detailed analysis of one selected variant (worksheets “CODE_graphOne”). Various column charts are generated, including the visualisation of the global results, the contribution of the life cycle modules, the contribution of the environmental impact indicators and the contribution of the constituting work sections.

At the building level, a similar structure is used with a subdivision in two worksheets: one for the comparison of all building variants (worksheet “BU_graphAll”) and one for the detailed analysis of one selected building variant (worksheet “BU_graphOne”). As for the building elements, various column charts are generated, such as the visualisation of the global results, the contribution of the life cycle modules, the contribution of the environmental impact indicators and the contribution of the constituting building elements.

6.2 Neighbourhood calculation model

To assess neighbourhoods, the existing building calculation model is adapted by including a number of additional worksheets (see Figure 6.1). The required adaptations are described in the subsequent subsections.

6.2.1 Additional databases

Two additional databases are added to collect the impact data related to land use and user transport respectively. The first database (worksheet “DB_LandUse”) includes the characterization factors for the environmental impacts of land occupation and transformation for various types of land use. The second database (worksheet “DB_UserTransport”) contains the financial and environmental impact data for transport by car, bicycle and public modes.

6.2.2 “Calculation modules” worksheets

Specific calculation modules are developed for the assessment of the financial and environmental impact of operational energy use, operational water use, primary land use and user transport. These modules are implemented in four worksheets: “MOD_Energy”, “MOD_Water”, “MOD_LandUse” and “MOD_UserTransp” respectively. The calculation methods and formulas used to assess these aspects are described in Chapter 5.

6.2.3 “External elements” worksheets

Additional worksheets are added at the level of the work sections (worksheets “(9-)+_WS”) and building elements (worksheets “(9-)+_EL”) to assess the financial and environmental impacts of external elements. More specifically, worksheets are implemented for the assessment of roads, bicycle paths, footpaths, parking facilities, squares, planted surfaces, piped and electrical services. The structure of these worksheets is identical to the structure of the other “Work sections” and “Building elements” worksheets (see Section 6.1.4).

6.2.4 “Neighbourhoods” worksheets

The “Composed objects” worksheets are extended with an additional level focussing on the neighbourhood scale. A similar structure to the “Buildings” worksheets is followed with a subdivision in two worksheets: “NE_Par” and “NE_Calc”. The first worksheet contains the input parameters of the analysed neighbourhoods. Parameters related to the neighbourhood layout and geometry, the constituting neighbourhood elements (including buildings and external elements) and the calculation of the operational water use, primary land use and user transport have to be defined. These parameters can be grouped in variants to allow for an easy selection and combination of pre-defined input data. Concerning the neighbourhood geometry, the input parameters are described in detail in Appendix C.

In the second worksheet “NE_Calc” the environmental and financial impacts of the neighbourhoods are calculated. The input parameters are automatically collected from the worksheet “NE_Par”. Based on the input parameters and the impact data for the buildings (worksheet “BU_Calc”) and external elements (worksheets “(9-)+_EL”), the financial and environmental impacts of the constituting neighbourhood elements are calculated for the various life cycle modules (from module A up to module C). The financial and environmental impacts of the neighbourhoods are consequently calculated as the sum of all constituting neighbourhood elements. Concerning the operational energy use, operational water use, primary land use and user transport (module B6 up to B9), the impact results are collected from the specific calculation modules.

6.2.5 Additional visualisations

Additional worksheets are added to visualise the results of the financial and environmental impact calculations of the external elements and neighbourhoods. The visualisation output is further illustrated in Chapter 7 and Chapter 8.

For the external elements, the visualisations are similar to the other building elements with a subdivision in two worksheets for each type of external element: one for the comparison of all variants of that external element (worksheets "(9-)+_graphAll") and one for the detailed analysis of one selected variant (worksheets "(9-)+_graphOne").

At the neighbourhood level, the same structure is used: worksheet "NE_graphAll" includes the comparison of all neighbourhood variants and worksheet "NE_graphOne" focuses on the detailed analysis of one selected neighbourhood variant (worksheet "NE_graphOne"). Various column charts are provided, such as the visualisation of the global results, the contribution of the life cycle modules, the contribution of the environmental impact indicators and the contribution of the constituting neighbourhood elements. Also on this level, the same graphical conventions are used as for the underlying scale levels.

6.3 Conclusions

The calculation model proposed follows a hierarchical structure in line with the principles of the element method for cost control, which allows an analysis of the financial and environmental impacts at various scale levels. Furthermore, this hierarchical calculation structure has been extended to neighbourhoods by adding an additional level on top of the existing building impact calculations.

The calculation model is implemented in a number of Excel spreadsheets allowing the control of all calculation steps and a detailed analysis of the impact contributors. Moreover, the spreadsheet tool can be used during the various stages of the design process as it enables both a detailed assessment and rough estimations based on the use of predefined building element variants and default values for various parameters.

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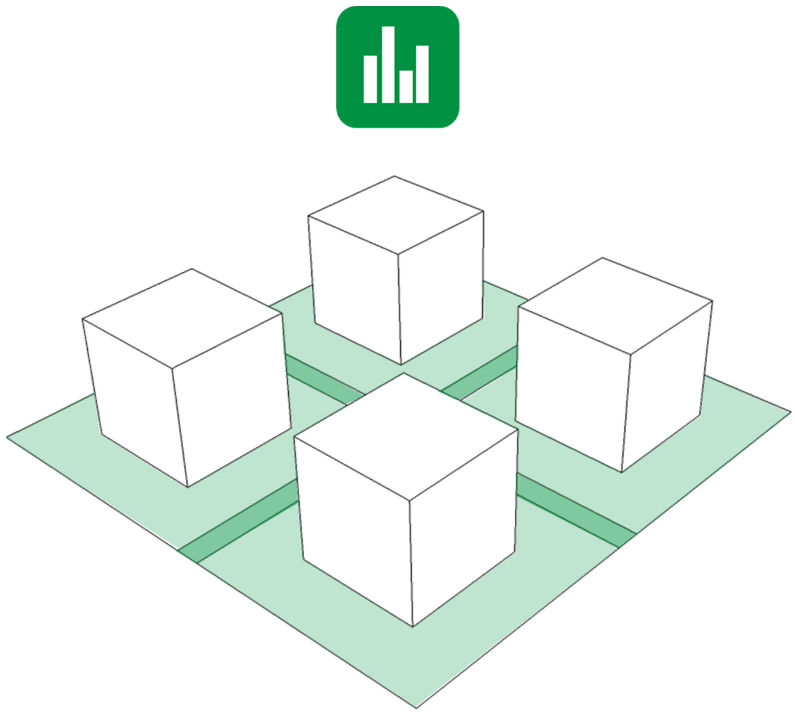
CHAPTER 7

Assessment of networks and open spaces

In this chapter, the financial and environmental impact of neighbourhood elements are assessed. The elements considered include networks (roads, bicycle paths, footpaths and utilities), open spaces (squares, parks and gardens) and parking facilities. These neighbourhood elements are implemented in the schematic neighbourhood models which are analysed in Chapter 8.

The E-LCA and LCC results of the assessment of road infrastructure have been discussed in a paper published in the International Journal of Life Cycle Assessment (Trigaux et al. 2016).



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7.1 Assessment of local roads

7.1.1 Description and declared unit

Various sections of a two-lane road for local traffic representative for Belgium are considered. Their composition is schematically represented in Figure 7.1 and summarised in Table 7.1. The road considered is five metres wide[1] and is composed of a geotextile, a sub-base, a base and a surface layer. Piped services (including the road gullies and connection to the storm sewer) and electrical services (including road lighting[2]) are considered in the road system. Five variants for the surface layer are compared, i.e. asphalt, concrete, reclaimed cobblestones, concrete paving stones and water-permeable concrete stones (Road 1 to 5). Furthermore, an alternative for the type of base and sub-base is considered, consisting of the use of crushed rubble instead of gravel (Road 6). The variant with water-permeable concrete stones is not provided with a sewer connection and the base and sub-base are adapted to allow for rainwater buffering.

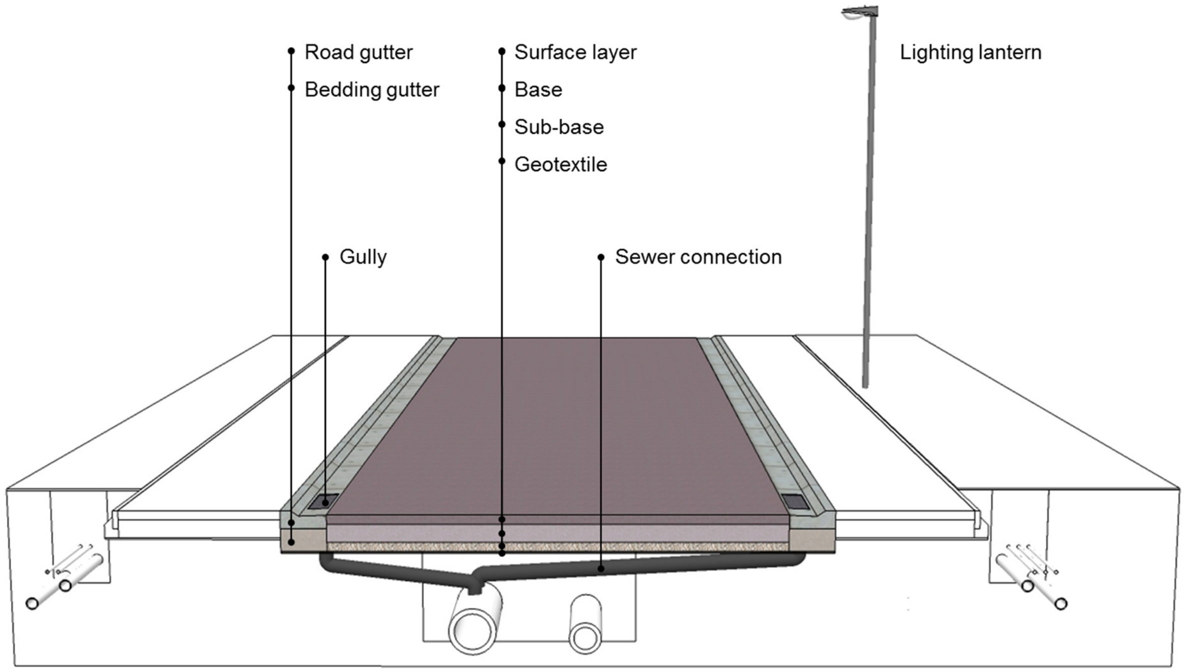

Figure 7.1: 3D section of the two-lane local road for local traffic[3], based on (Trigaux et al. 2016).

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[1] The road width is an input parameter which can be modified in the spreadsheet tool.

[2] Although lighting is also required for the adjacent bicycle paths and footpaths, the impact of road lighting is in this research fully allocated to the road.

[3] In the analysed road section, drinking water and gas pipes, electric and data cables are located on both sides of the road to allow for an easy access to these utilities. When there is a lack of space, utilities can be located under the footpath or bicycle path. This however requires a (partial) demolition of the paved area when utilities need to be replaced.

Table 7.1: Composition of the road variants (Trigaux et al. 2016).

Composition	Road 1_ asphalt	Road 2_ concrete	Road 3_ cobblestones	Road 4_ concrete stones	Road 5_ permeable concrete stones	Road 6_ asphalt_ crushed rubble
Geotextile	Polypropylene					
Sub-base	Crushed gravel – type II* (10 cm)				Crushed gravel – type II* (20 cm)	Crushed mixed rubble –type II* (10 cm)
Base	Cement bound base – crushed gravel – type IIA* (20 cm)				Porous lean concrete – limestone (20 cm)	Cement bound base – crushed concrete rubble – type IIA* (20 cm)
Surface layer	Asphalt (binder course 6 cm + surface course 4 cm)	Concrete (20 cm)	Reclaimed porphyry cobblestones (14x14x14 cm) + sand layer (7.5 cm)	Concrete paving stones (22x11x10 cm) + sand layer (3 cm)	Concrete paving stones (22x16.5x10 cm) with enlarged joints + gravel layer (3 cm)	Asphalt (binder course 6 cm + surface course 4 cm)
Road gutter	Concrete road gutter (type IIIE*) + bedding (lean concrete)					
Gully and connection to sewer	Cast iron gully + connecting pipe (PVC Ø 160 mm)				No gully and connection to sewer	Cast iron gully + connecting pipe (PVC Ø 160 mm)
Road lighting	Galvanised steel column + lantern 70 W					

*In accordance with the Flemish specifications for road construction (Flemish Government 2010).

Regarding the declared unit, the impact of the two-lane road is assessed per metre road. A life span of 60 years is assumed for local road infrastructure, corresponding to the average technical life span of sewer pipes (Egyed et al. 2008; Oosterom and Hermans 2013), as the replacement of sewer pipes often results in a complete reconstruction of the road.

Although the road composition influences various quality aspects such as the driving comfort, noise generation, rolling resistance and safety, this research does not include an in-depth evaluation of those performances.

7.1.2 Life cycle scenarios

Various scenarios are defined for maintenance, replacement processes and energy use for road lighting. Cleaning of roads and sewers is not considered because financial and environmental data are lacking. It is however expected that the impact of these activities is negligible as the cleaning frequencies for roads are much lower than for indoor cleaning.

Scenarios for maintenance and replacements of road components are based on publications from the road construction sector and existing LCA studies (Wijnants 2014)[4]. As the focus of this research is on local road infrastructure, relatively low replacement frequencies are assumed for the surface layers, i.e. 30 years for asphalt and 40 years for concrete, concrete tiles and concrete paving stones. For the cobblestone, no replacement is considered during the road life span but a relay of the stones every 20 years is assumed. It should however be noticed that for asphalt top layers, higher replacement frequencies of 12 to 20 years are found in the literature for roads with a more intensive traffic load (Gschösser 2011). The results of the comparison between various road surface layers are therefore only applicable for low traffic roads and should not be interpreted in general terms. An overview of the maintenance and replacement scenarios is provided in Table 7.2. The same scenarios are assumed for all road infrastructure elements, utilities and open spaces analysed. Apart from the replacement of specific work sections[5], no reconstruction of the road occurs during the neighbourhood life span as both the roads and the neighbourhood have a life span of 60 years.

The energy consumption for road lighting is calculated assuming energy efficient lighting lanterns of 70 W, placed every 20 m on one side of the road, and with a yearly average lighting period of 12 hours per day[6]. This results in an electricity consumption of about 15 kWh per metre road per year.

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[4] This master thesis is consultable in the Campus Library Arenberg in Herverlee (Leuven). The main sources used for the maintenance and replacement scenarios are (CROW 2003; Benelux Bitume 2005; Van Timmeren 2006; Egyed et al. 2008; Enexis 2009a; Enexis 2009b; Flemish Government 2010; Moes and Cuperus 2010; Gschösser 2011; IenM 2011; KWR 2011; Bosch 2012; Oosterom and Hermans 2013).

[5] Work sections are defined as the constituting components of building elements (see Chapter 4). Examples of road work sections are the road surface layer, base and sub-base.

[6] The type of lighting, distance between the lighting lanterns and lighting period are input parameters which can be modified. A detailed study of the influence of these parameters is however not included in this research.

Table 7.2: Maintenance and replacement scenarios, applied to the road infrastructure, utilities and open spaces, based on data from (Wijnants 2014).

Work sections	Maintenance	Replacement[7]
Surface layer		
Asphalt	5 % repair of asphalt top layer - 5 years	30 years
Concrete	Fissure filling and 0.1 % repair - 10 years	40 years
Cobblestones	Relay - 20 year	-
Concrete tiles	Relay and 10 % new tiles - 20 years	40 years
Concrete paving stones	Relay and 10 % new stones - 20 years	40 years
Road marking		
Solvent paint	-	1 year
Cold plastic coating	-	3 years
Pipes services		
Sewer pipes	-	60 years
Drinking water and gas pipes	-	100 years
Electrical services		
Lighting column	-	40 years
Lighting lantern	-	20 years
Electric cable	-	80 years
Data cable	-	20 years

7.1.3 Environmental impact

The life cycle environmental cost of the roads is shown in Figure 7.2. The environmental data used for the calculations are described in Chapter 3. The Life Cycle Impact Assessment (LCIA) results are subdivided per life cycle module and expressed in euro per metre road (present value over a life span of 60 years). The analysis of the first road section (i.e. a bituminous asphalt road) reveals that the energy use for road lighting and the production phase contribute most to the environmental profile and represent respectively 32% and 25% of the life cycle environmental cost of the road. Other significant contributors are the replacement of the work sections and the demolition phase which contribute to 17% and 10% of the life cycle environmental cost respectively. The environmental impact caused by replacements of the work sections is mainly due to the replacement of the asphalt surface layer every 30 years. The latter emphasizes the importance of the replacement strategies for the surface layers. Finally, the construction, maintenance, waste transport, waste processing and waste disposal have a negligible impact, with a contribution of less than 5% to the life cycle environmental cost.

[7] At the end of life of the road (60 years) no residual value is considered for the components that have not yet reached the end of their service life as it is assumed that the whole road is being demolished.

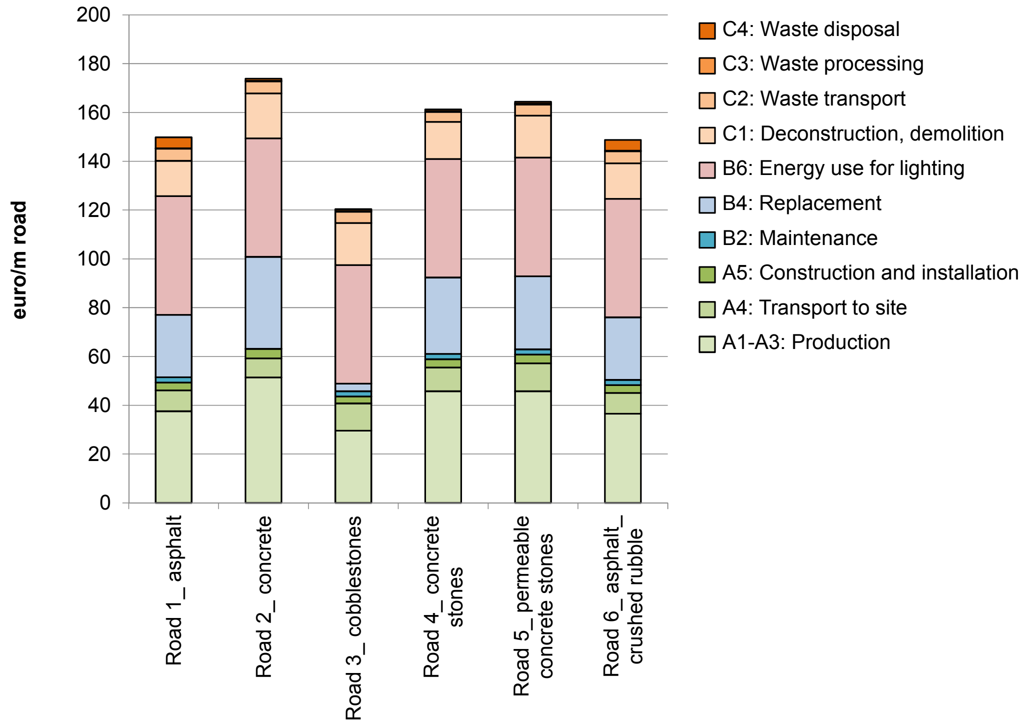

Figure 7.2: Life cycle environmental cost of the road variants, subdivided per life cycle module.

The analysis of the various work sections (Figure 7.3) reveals that the asphalt layers of the first road section (Road 1) cause 31% of the life cycle environmental cost. Compared with these surface layers, the base and sub-base have a low environmental impact (respectively 12% and 5% of the life cycle impact) as there is no maintenance or replacement of these during the life span of the road. The impact of the lighting lanterns and columns represent only 4% of the life cycle impact which is much lower than the impact resulting from the energy use for lighting.

When comparing the asphalt surface layer with four alternative surface layers (Figure 7.2 and Figure 7.3), the cobblestone surface layer causes the lowest environmental cost, i.e. a reduction of 67%, mainly due to the use of reclaimed cobblestones. Compared to asphalt, the surface layers in concrete, concrete paving stones and permeable concrete paving stones have a higher environmental impact of respectively 47%, 24% and 18% due to a higher environmental cost for the production of concrete based products. For the variant in permeable concrete stones, the impact reduction resulting from the absence of gullies and sewer connection is largely compensated by an increase in the impact of the road base and subbase. The reason is the use of a base in porous lean concrete (instead of cement bonded crushed gravel) and a thicker sub-base, which is required for the rainwater buffering. Finally, an alternative for the type of base and sub-base is analysed (Road 6). Using rubble instead of primary gravel for the base and sub-base leads to a small reduction of 4% of the environmental cost of these work sections. This is because the environmental cost of gravel mainly results from the crushing process which is also required for the production of rubble[8].

[8] The crushing process of rubble is allocated to the current system under study, in accordance to EN 15804 and EN 15978 (CEN 2011; CEN 2013).

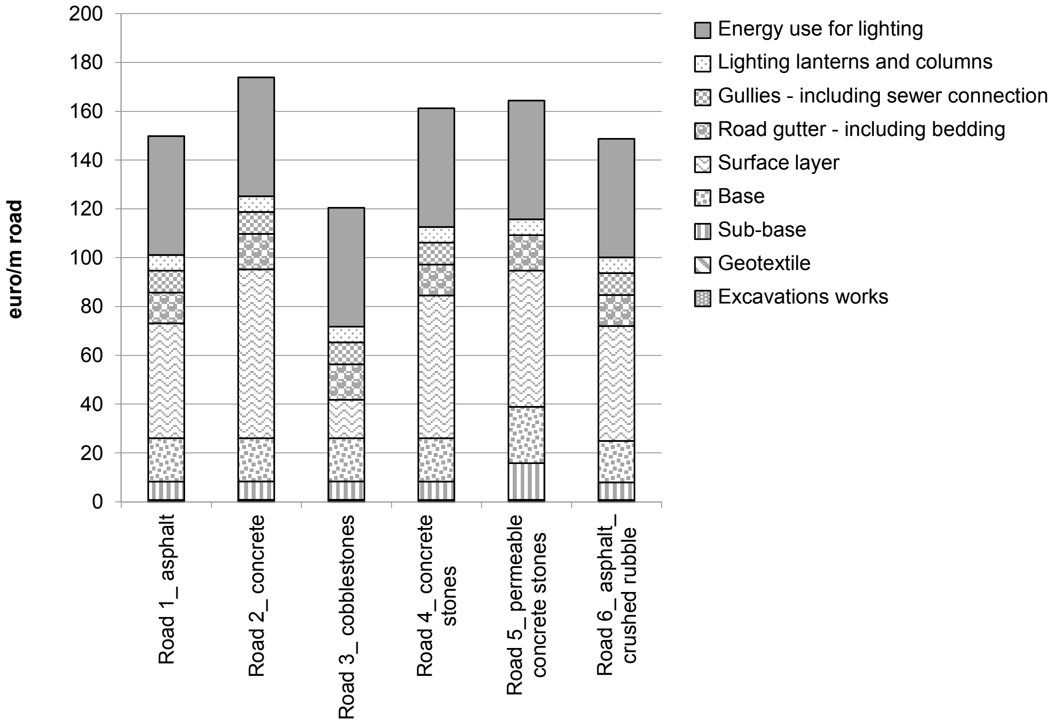

Figure 7.3: Life cycle environmental cost of the road variants, subdivided per work section.

As the road alternatives only differ in a few work sections from the asphalt road, the difference in environmental cost compared to the reference road is limited to 20%. The highest and lowest environmental cost are obtained for respectively the concrete road (+16% compared to the asphalt road) and the cobblestone road (-20% compared to the asphalt road).

The life cycle environmental cost of the roads is shown per impact category in Figure 7.4 and Figure 7.5. The most contributing impact categories are global warming, particulate matter, human toxicity (cancer effects) and eutrophication. These categories are responsible for respectively 57%, 17%, 10% and 8% of the life cycle environmental cost of the asphalt road. Other impact categories have a negligible contribution, i.e. lower than 5% of the life cycle environmental cost. The main drivers for the categories global warming and eutrophication are the energy use for lighting and the surface layer (Figure 7.5). In addition to these, other significant contributors for the categories particulate matter and human toxicity (cancer effects) are respectively the base and gullies. Concerning global warming, the high contribution to the environmental cost is a result of the high valuation of this impact category in the recent update of the MMG monetisation method (De Nocker and Debacker 2015)[9]. In consequence, conclusions drawn based on the environmental cost are often similar to those based on the impact on global warming solely. As the valuation methods are constantly under review, the importance of the monetisation factors should be considered in future updates of the MMG method.

[9] In the updated method, global warming is valued 0.1 €/kg CO_2 equiv. for the central scenario, instead of 0.06 €/kg CO_2 equiv. in the original method (Allacker et al. 2013; De Nocker and Debacker 2015).

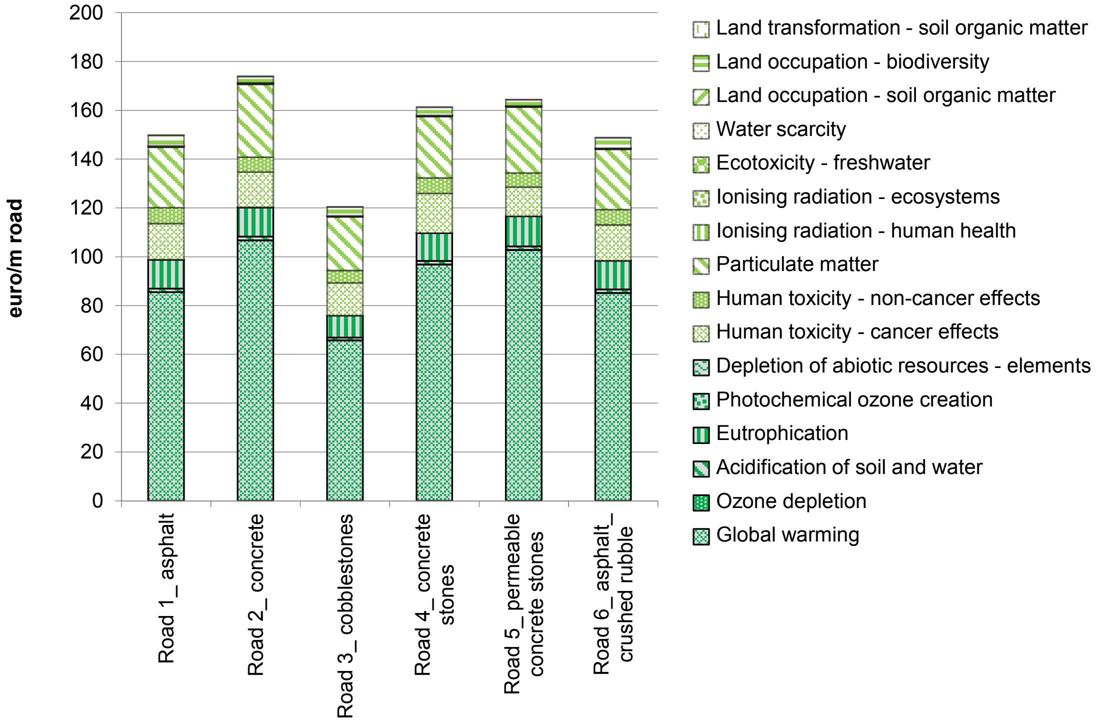

Figure 7.4: Life cycle environmental cost of the road variants , subdivided per impact category.

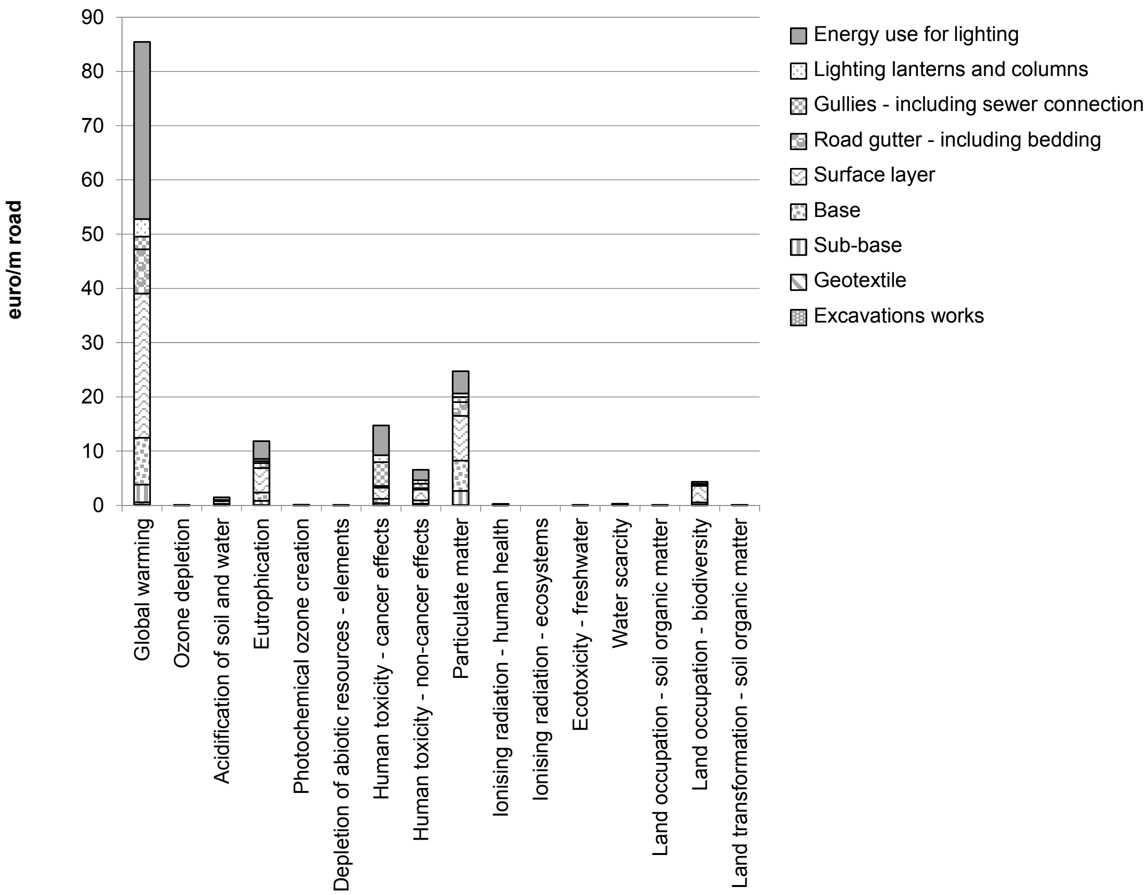

Figure 7.5: Life cycle environmental cost of the asphalt road variant (Road 1_asphalt), subdivided per impact category and work section.

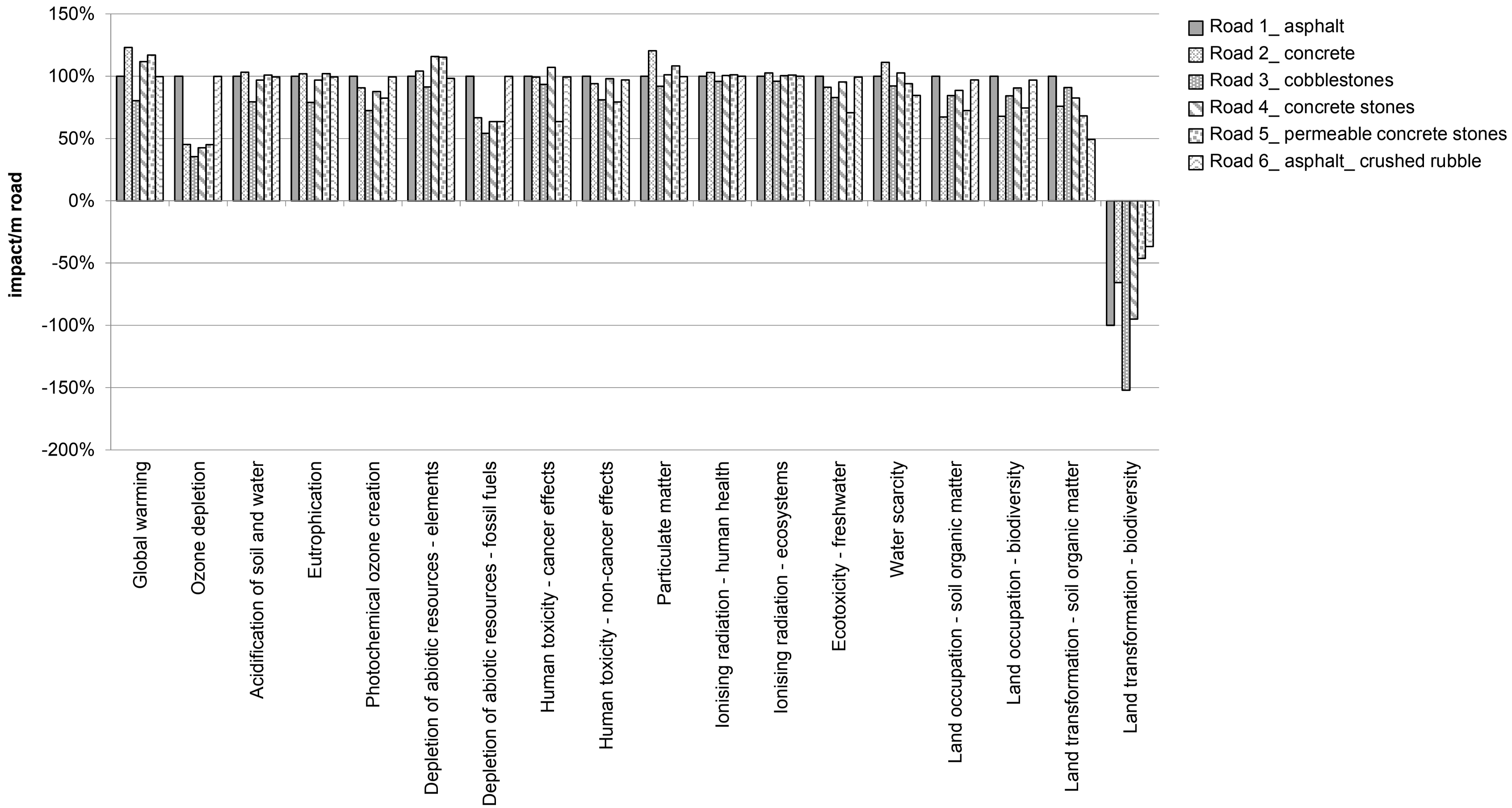

Figure 7.6: Life cycle environmental impacts of the road variants, subdivided per impact category. The results are relatively compared to the impact of the road with an asphalt surface layer (Road 1_asphalt)[10].

[10] A negative impact is obtained for the category land use transformation(biodiversity) due to the use of mineral products, such as gravel and sand. This is a consequence of the transformation impact linked to the mineral extraction site, which results in an increase in land quality compared to the original type of land use (assumed as "unknown").

A comparison between the various road variants per impact category (Figure 7.6) reveals that the preferred road variant depends on the analysed impact indicator. The cobblestone road has the lowest impact for most impact categories, but not for 7 of the 18 impact indicators. First, the road with permeable paving stones has the lowest impact for the indicators human toxicity and ecotoxicity, due to the absence of cast iron gullies which have a high contribution to these impact categories. Second, the use of crushed rubble instead of crushed gravel for the base and sub-base results in the highest impact reduction for the indicators water scarcity and land transformation (soil organic matter), although it has only a limited influence on other impact categories. Third, the concrete road has the lowest impact on soil organic matter and biodiversity due to land use occupation.

7.1.4 Financial impact

Beside the analysis of the environmental impact, the life cycle financial cost of the roads is calculated (Figure 7.7 and Figure 7.8). The financial data used for the calculations are described in Chapter 3. The analysis of the asphalt road (Road 1) reveals that the investment cost is the highest contributor (50% of the life cycle financial cost) followed by the replacement cost of work sections (23% of the life cycle financial cost). The maintenance, demolition and waste treatment have a negligible cost with a contribution of about 5% to the life cycle financial cost. In contrast to the environmental cost, the financial cost of energy use for lighting is relatively limited, i.e. 13% of the life cycle financial cost. Regarding the contribution of the work sections, the asphalt layers are responsible for 40% of the financial cost. The base and sub-base contribute much less with respectively 12% and 3% of the life cycle cost as there is no maintenance or replacement of these during the life span of the road.

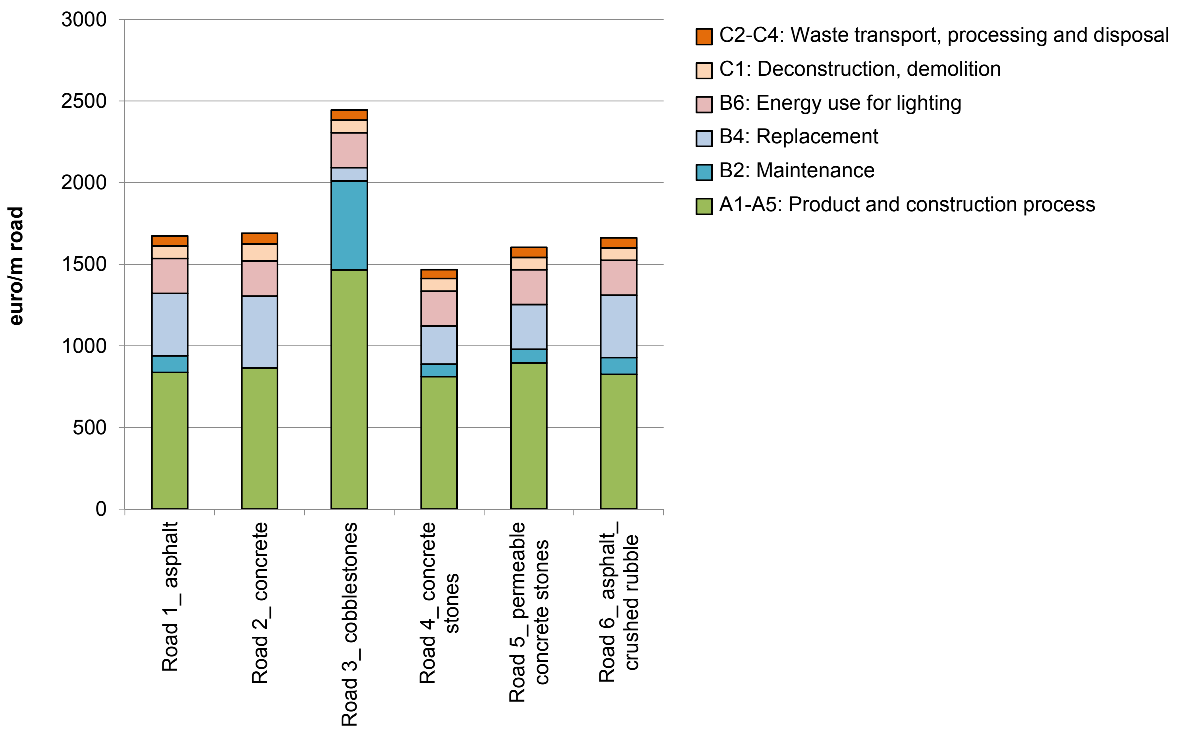

Figure 7.7: Life cycle financial cost of the road variants, subdivided per life cycle module.

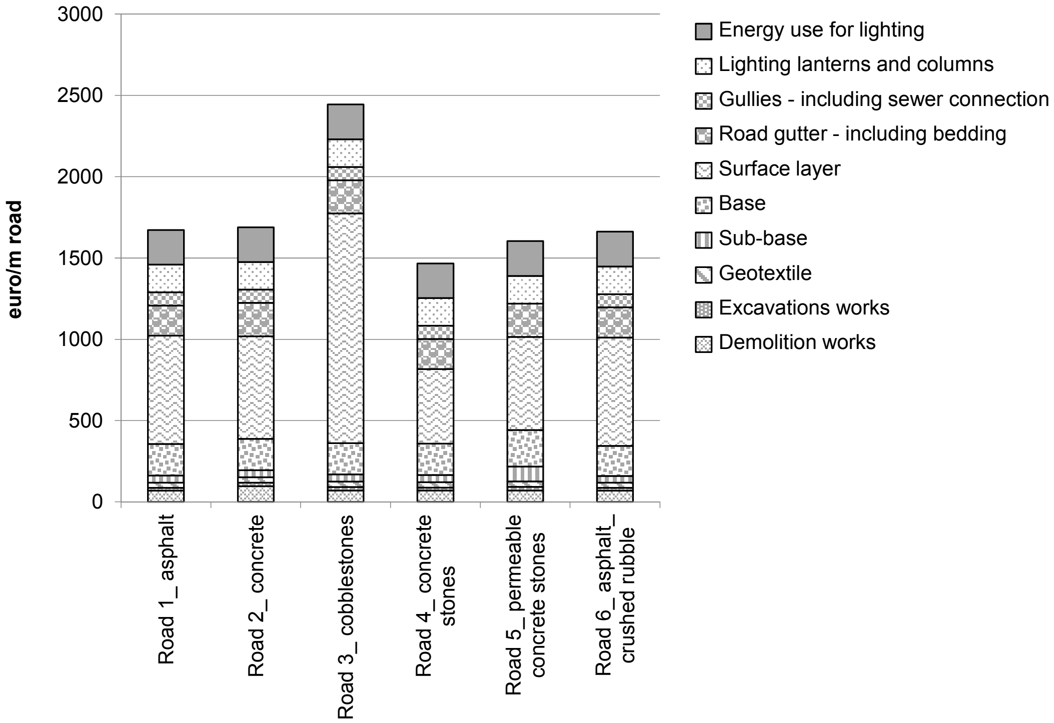

Figure 7.8: Life cycle financial cost of the road variants , subdivided per work section.

The comparison of the life cycle financial cost of the alternative surface layers (Road 1-5) shows a quite different picture than for the environmental cost. The cobblestone surface layer has the highest financial cost, about two times higher compared to the asphalt surface layer. This is due to the high market price of reclaimed cobblestones and the high labour cost for laying these. Compared to asphalt, the concrete surface layer has a 5% lower life cycle financial cost but this reduction is compensated by the higher demolition cost of concrete roads. The surface layers in non-permeable and permeable concrete paving stones are respectively 31% and 14% less expensive than the asphalt surface layer, due to a lower maintenance and replacement cost. However, for the permeable concrete stones, the lower financial cost of the surface layer is compensated by an increase in the cost of the (thicker) sub-base and the road base, consisting of porous lean concrete instead of cement bound crushed gravel. Finally, the use of crushed rubble for the road base and sub-base (Road 6) results in a small decrease of 5% of the financial cost of these work sections.

As for the environmental cost, differences in life cycle financial cost between the road variants are rather limited, i.e. not exceeding 15% compared to the asphalt road. Only the cobblestone road shows a bigger difference with a financial cost that is 46% higher than the asphalt variant.

7.1.5 Total cost

Based on the life cycle financial and environmental cost, the total cost of the road variants is calculated (Figure 7.9). The results show a similar picture as for the financial cost because the environmental cost contributes to less than 10% of the total cost. As the internalisation of the external environmental cost does not influence the decisions based on financial cost, the results for the total cost are not reported separately for the assessment of other neighbourhood elements in this chapter.

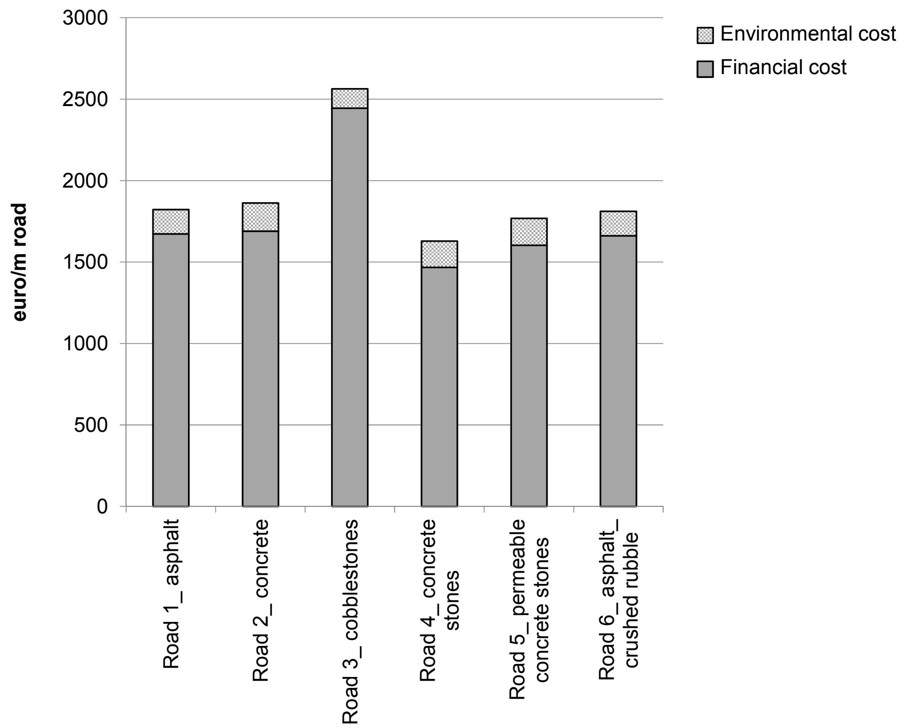

Figure 7.9: Life cycle total cost of the road variants, subdivided in financial and environmental cost.

7.2 Assessment of bicycle paths

7.2.1 Description and declared unit

The bicycle paths are assumed 1.75 metres wide[11] and are composed of a geotextile, a base and a surface layer (Table 7.3 and Figure 7.10). Three variants for the surface layer are compared, i.e. asphalt, concrete and concrete paving stones (Bicycle path 1 to 3). As red coloured bicycle paths are often used by municipalities for security reasons, four alternative colouring systems are analysed: red road paint on asphalt, red cold plastic coating on asphalt, red pigmented concrete and red pigmented concrete paving stones (Bicycle path 4 to 7). In analogy to the roads, the impact of the bicycle paths is assessed per metre and a life span of 60 years is assumed.

[11] Recommended width for a one-way bicycle path (Mobiel Vlaanderen 2017)

Table 7.3: Composition of the bicycle path variants, based on (Trigaux et al. 2016).

Composition	**Bicycle path 1_asphalt**	**Bicycle path 2_concrete**	**Bicycle path 3_concrete stones**	**Bicycle path 4_asphalt_red paint**	**Bicycle path 5_asphalt_red coating**	**Bicycle path 6_red concrete**	**Bicycle path 7_red concrete stones**
Geotextile	Polypropylene						
Base	Cement bound base – crushed gravel – type IIA* (20 cm)						
Surface layer	Asphalt (binder course 6 cm + surface course 4 cm)	Concrete (16 cm)	Concrete paving stones (22x11x10 cm) + sand layer (3 cm)	Asphalt (binder course 6 cm + surface course 4cm)	Asphalt (binder course 6 cm + surface course 4 cm)	Red concrete (16 cm)	Red concrete paving stones (22x11x10 cm) + sand layer (3 cm)
Paint/coating	-			Red solvent paint, inclusive glass beads	Red cold plastic coating, inclusive glass beads	-	
Kerbstone	Concrete kerbstone (type ID4*) + bedding (lean concrete)						

*In accordance with the Flemish specifications for road construction (Flemish Government 2010).

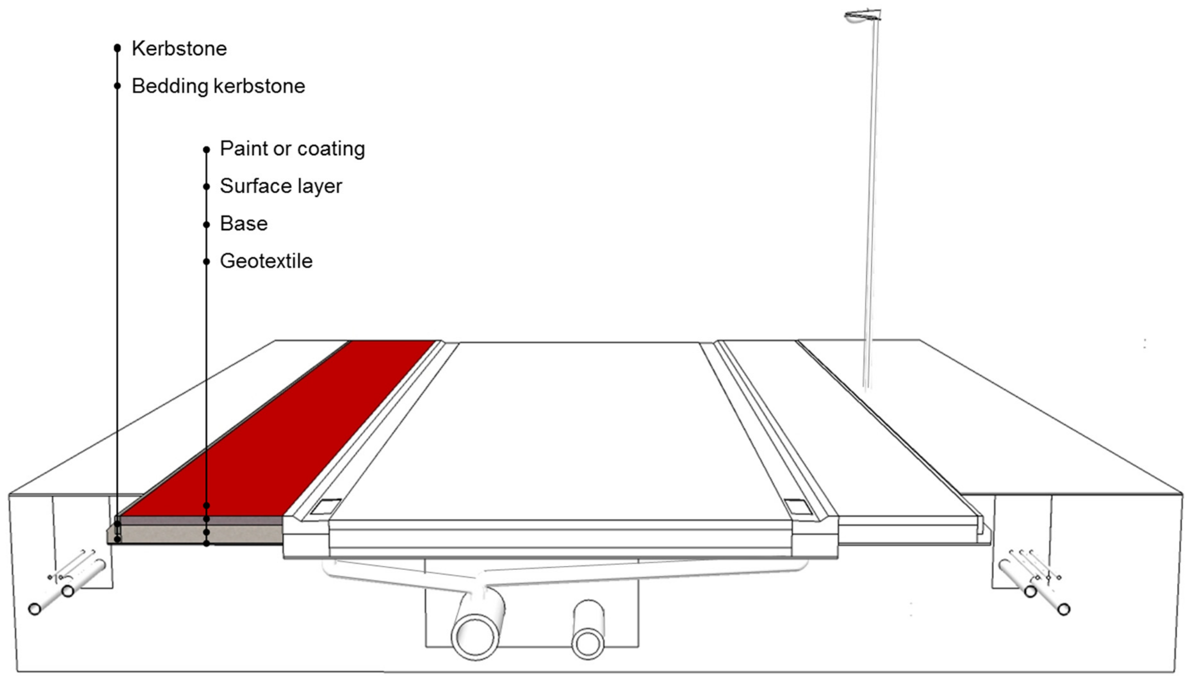

Figure 7.10: 3D section of the bicycle path.

7.2.2 Life cycle scenarios

The same scenarios as for the roads are assumed because the bicycle paths are not physically separated from car traffic. An overview of the maintenance and replacement scenarios is provided in Table 7.2 (see section 7.1.2).

7.2.3 Environmental impact

The LCIA results of the bicycle paths are shown in Figure 7.11. Significant differences in environmental cost are identified. When considering uncoloured bicycle paths (Bicycle path 1 to 3), the asphalt bicycle path causes the lowest life cycle environmental impact due to a lower production impact compared to surface layers in concrete. The life cycle environmental cost of bicycle paths consisting of concrete and concrete paving stones is respectively 13% and 17% higher compared to the asphalt variant.

The analysis of the red coloured bicycle paths (Bicycle path 4 to 7) reveals that using red pigments in concrete and concrete paving stones results in a negligible increase in environmental cost, not exceeding 0.1%. Road marking on the other hand has a major impact as the results show a 45% higher environmental cost for a bicycle path with red road paint and an increase of 242% when using red cold plastic coating, compared to an uncoloured asphalt bicycle path. Despite the higher replacement frequency of road paint (1 year versus 3 years), the environmental impact of the variant with a cold plastic coating is much higher than of the one with road paint, due to a larger dosage (3.35kg/m² versus 0.7kg/m²) and the production impact of the polymethyl methacrylate binder used in cold plastic coating.

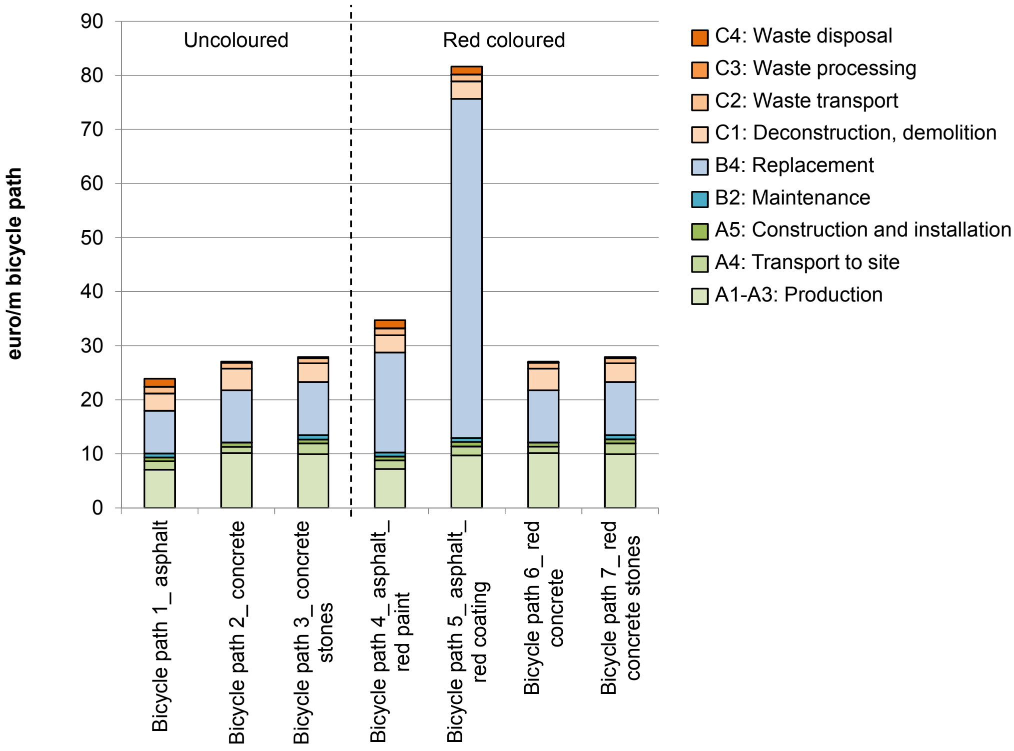

Figure 7.11: Life cycle environmental cost of the bicycle path variants, subdivided per life cycle module.

7.2.4 Financial impact

The life cycle financial cost of the bicycle path variants is shown in Figure 7.12. Differences but also similarities are identified, compared to the environmental impact assessment.

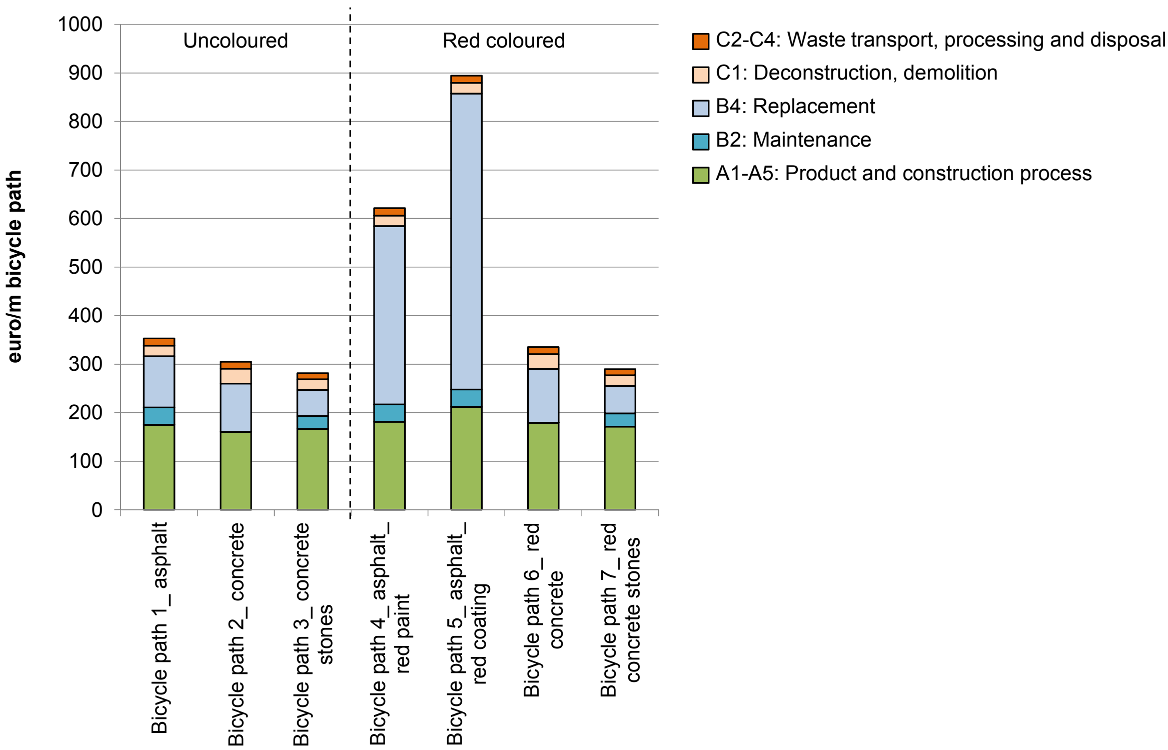

Figure 7.12: Life cycle financial cost of the bicycle path variants, subdivided per life cycle module.

Among the uncoloured bicycle paths, the asphalt path has the highest financial cost. The life cycle financial cost of the ones consisting of concrete and concrete paving stones is respectively 14 and 20% lower than the asphalt variant. Similar to the environmental impact, the bicycle paths with road marking have a higher financial cost (i.e. up to 153% higher compared to the uncoloured paths) due to the high frequency of repainting and recoating. While the cost of red and standard concrete paving stones is almost similar, the life cycle cost of red concrete is 10% higher than the life cycle cost of the uncoloured concrete path.

7.3 Assessment of footpaths

7.3.1 Description and declared unit

The footpaths are similar to the bicycle paths. The footpaths are 1.5 metres wide[12] and are composed of a geotextile, a base and a surface layer (Table 7.4 and Figure 7.13). Several variants for the surface layer are compared, including asphalt, concrete, reclaimed cobblestones, concrete paving stones, water-permeable concrete stones and concrete tiles (Footpath 1 to 6). The use of an alternative type of base, consisting of crushed rubble is considered too (Footpath 7). Concerning the variant with water-permeable concrete stones, a sub-base and unbound base are provided to allow for rainwater buffering. Regarding the declared unit, the impact of the footpaths is assessed per metre and a life span of 60 years is assumed.

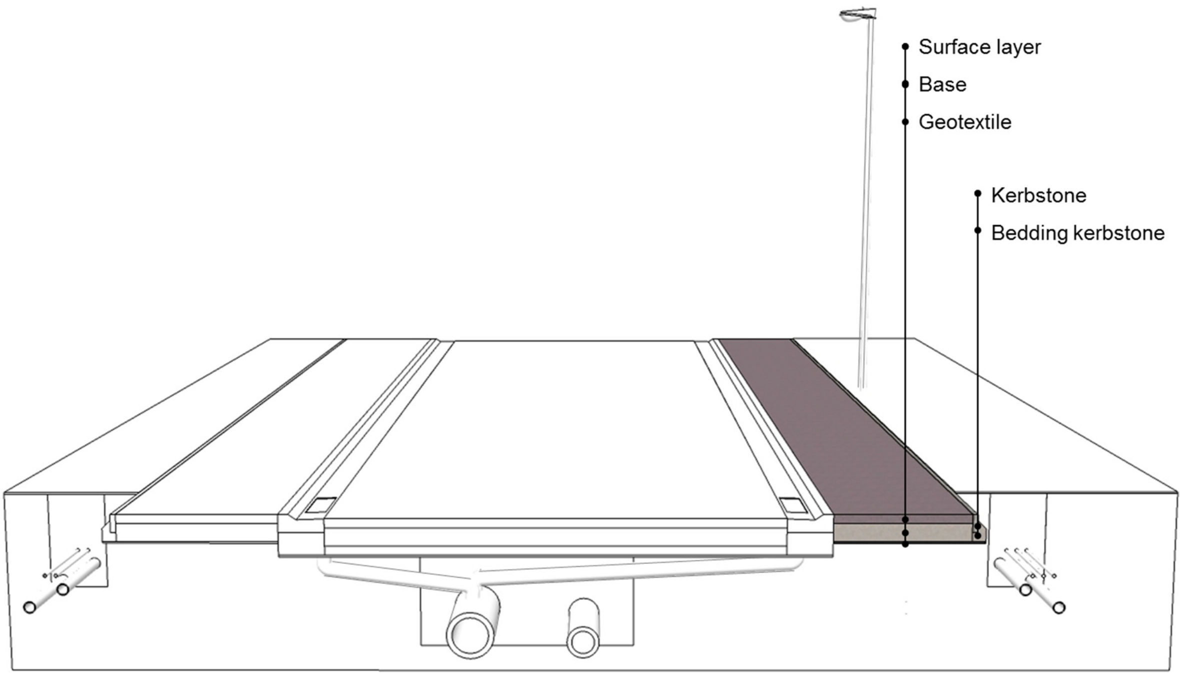

Figure 7.13: 3D section of the footpath.

[12] Minimum width as recommended by (Agentschap Wegen & Verkeer 2014)

Table 7.4: Composition of the footpath variants.

Composition	**Footpath 1_asphalt**	**Footpath 2_concrete**	**Footpath 3_cobblestones**	**Footpath 4_concrete stones**	**Footpath 5_permeable concrete stones**	**Footpath 6_concrete tiles**	**Footpath 7_asphalt_crushed rubble**
Geotextile	Polypropylene						
Sub-base	-				Crushed gravel – type II* (20 cm)	-	
Base	Cement bound base – crushed gravel – type IIA* (20 cm)				Unbound base – crushed gravel – type II* (20 cm)	Cement bound base – crushed gravel – type IIA* (20 cm)	Cement bound base – crushed concrete rubble – type IIA* (20 cm)
Surface layer	Asphalt (binder course 6 cm + surface course 4 cm)	Concrete (16 cm)	Reclaimed porphyry cobblestones (14x14x14 cm) + sand layer (7.5 cm)	Concrete paving stones (22x11x10 cm) + sand layer (3 cm)	Concrete paving stones (22x16.5x10 cm) with enlarged joints + gravel layer (3 cm)	Concrete tiles (40x40x4 cm) + sand layer (3 cm)	Asphalt (binder course 6 cm + surface course 4 cm)
Kerbstone	Concrete kerbstone (type ID4*) + bedding (lean concrete)						

*In accordance with the Flemish specifications for road construction (Flemish Government 2010).

7.3.2 Life cycle scenarios

The same scenarios as for the roads are used because the footpaths are not physically separated from car traffic. An overview of the maintenance and replacement scenarios is provided in Table 7.2 (see section 7.1.2).

7.3.3 Environmental impact

The results of the environmental impact assessment (Figure 7.14) show similar trends as for the assessment of the roads. First, the lowest life cycle environmental cost is obtained for the variant with reclaimed cobblestones, which impact is 44% lower compared to an asphalt footpath. Second, most variants consisting of concrete based surface layers have a higher life cycle environmental cost, due to the higher impact of production. Compared to the asphalt footpath, the variants with a surface layer in concrete, concrete paving stones and permeable concrete paving stones have a life cycle environmental cost that is respectively 13%, 17% and 30% higher. Only the variant with concrete tiles has a 16% lower life cycle impact compared to the asphalt variant, due to the limited thickness of the tiles. Third, the footpath with permeable concrete stones has the highest life cycle environmental cost as its composition includes both a base and sub-base. Finally, a negligible environmental impact reduction is obtained when using a base consisting of crushed rubble instead of gravel.

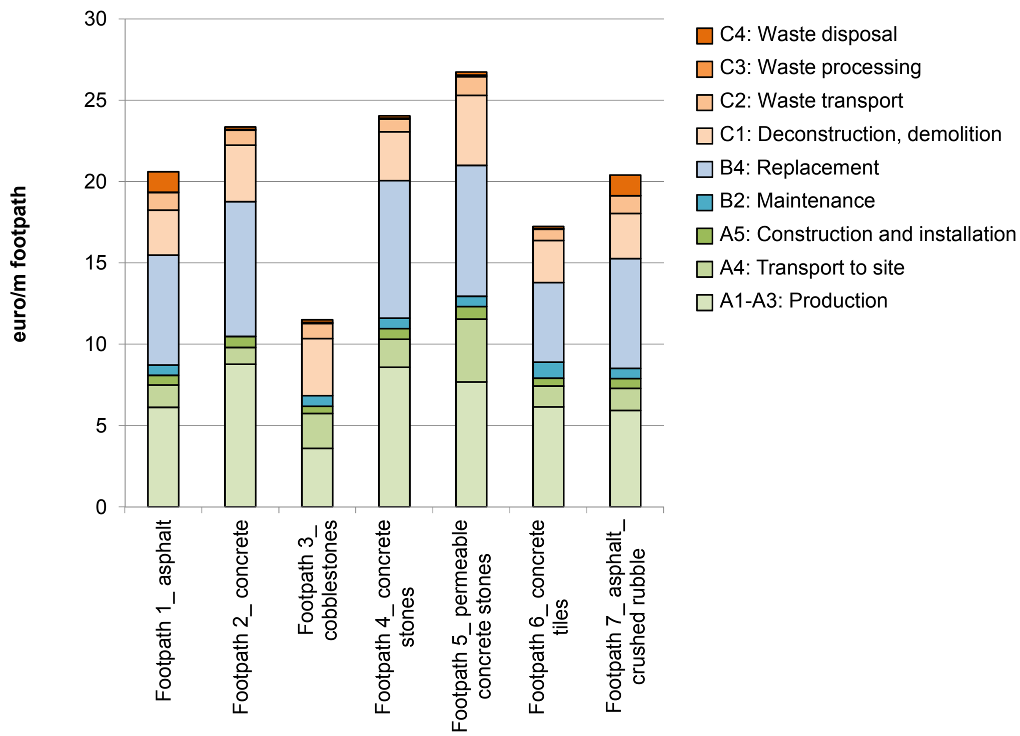

Figure 7.14: Life cycle environmental cost of the footpath variants, subdivided per life cycle module.

7.3.4 Financial impact

The financial impact assessment of the footpaths (Figure 7.15) also show several similarities with the assessment of the roads. First, the variant with the cobblestone surface layer has the highest life cycle financial cost, i.e. 75% higher compared to the asphalt variant. Second, the variants consisting of concrete based surface layers have a lower life cycle financial impact due to lower maintenance and replacement costs. Compared to the asphalt footpath, the variants with a surface layer in concrete, concrete paving stones, permeable concrete paving stones and concrete tiles have a life cycle financial cost that is respectively 13%, 20%, 10% and 9% lower. Finally, a negligible financial impact reduction is obtained when using a base consisting of crushed rubble instead of gravel.

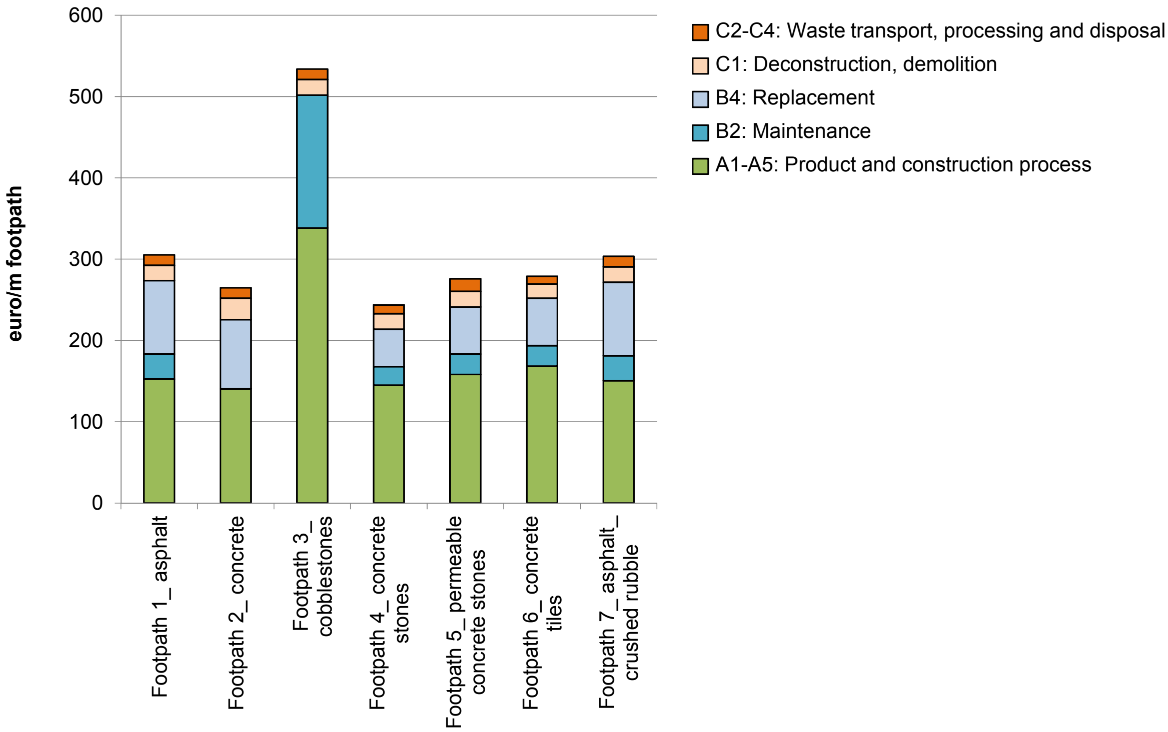

Figure 7.15: Life cycle financial cost of the footpath variants, subdivided per life cycle module.

7.4 Assessment of utilities

7.4.1 Description and declared unit

The utilities considered consist of piped services (drinking water, gas and sewer pipes) and electrical services (electric and data cables). These are presented in Figure 7.16 and summarised in Table 7.5. The sewer pipes are located under the road section, while the drinking water and gas pipes, electric and data cables are located on both sides of the road to allow for an easy access to these. The excavations and backfilling, sand bed and sand surround for sewer pipes are included in the analysis.

Regarding the sewer system, a standard variant consisting of a concrete storm sewer pipe and a vitrified clay sanitary sewer pipe is considered (Utilities 1_standard sewer). This is compared to an alternative consisting of polyvinylchloride (PVC) pipes (Utilities 2_PVC sewer) and one consisting of lightweight ribbed polypropylene (PP) pipes (Utilities 3_PP sewer).

Concerning the declared unit, the impact of the utilities is assessed per metre of network. A life span of 60 years is assumed as the replacement of the road and utilities are often carried out simultaneously.

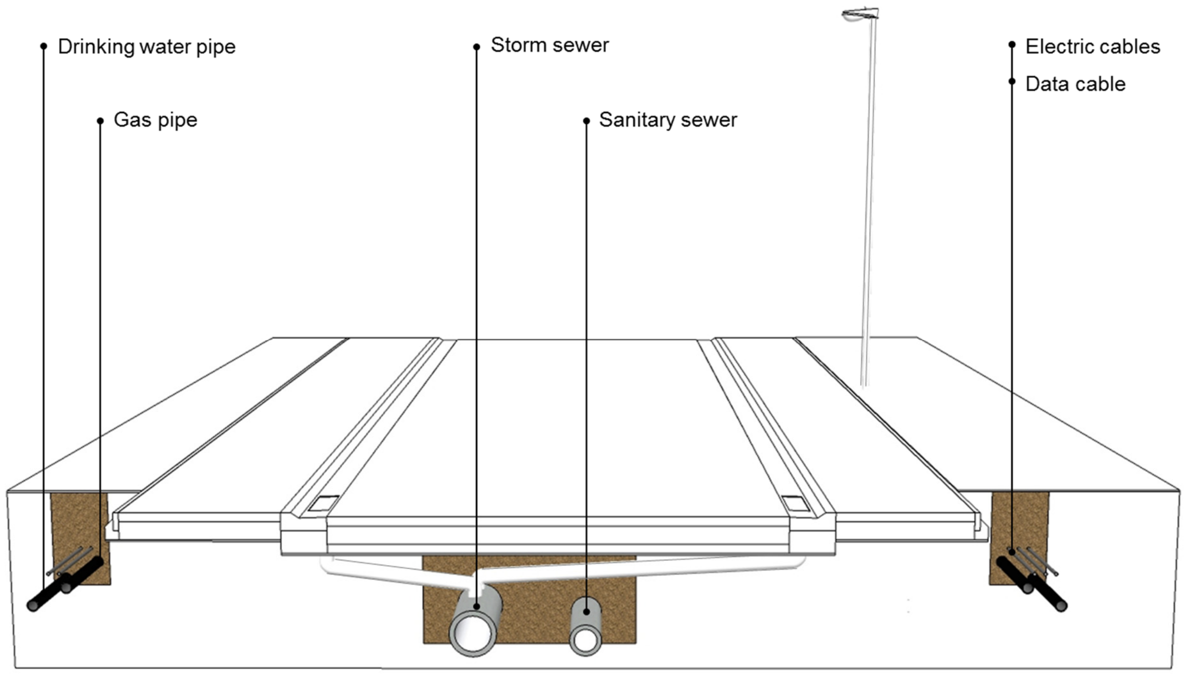

Figure 7.16: 3D section of the utilities.

Table 7.5: Composition of the variants for the utilities, based on (Trigaux et al. 2016).

Composition	**Utilities 1_standard sewer**	**Utilities 2_PVC sewer**	**Utilities 3_PP sewer**
Piped services			
Storm sewer	Concrete pipe (Ø 400mm) + sand bed and sand surround	PVC pipe (Ø 400mm) + sand bed and sand surround	Ribbed PP pipe (Ø 400mm) + sand bed and sand surround
Sanitary sewer	Vitrified clay pipe (Ø 250mm) + sand bed and sand surround	PVC pipe (Ø 250mm) + sand bed and sand surround	Ribbed PP pipe (Ø 250mm) + sand bed and sand surround
Gas pipe	HDPE pipe (Ø 110mm)		
Drinking water pipe	HDPE pipe (Ø 110mm)		
Electrical services			
Electric cable	Low voltage electric cable EXAVB-F2 (4x70mm²)		
Electric cable road lighting	Low voltage electric cable (4x25mm² +16mm² ground wire)		
Data cable	Fibre glass data cable (Ø 14mm)		

7.4.2 Life cycle scenarios

The life cycle scenarios are summarized in Table 7.2 (see section 7.1.2). Except the data cables, which have a life span of 20 years, the utilities have a life span of 60 years or more and are therefore not replaced during the considered period of analysis.

7.4.3 Environmental impact

The life cycle environmental cost is shown in Figure 7.17. The production phase is the highest contributor and represents 60% of the life cycle environmental cost of the standard variant (Utilities 1_standard sewer). Replacements have a low contribution to the environmental impact due to the long life span of utilities (only the data cables are replaced every 20 years).

Concerning the contribution of the work sections (Figure 7.18), the impact of the electric and data cables is remarkably high, i.e. 45% of the life cycle environmental cost in the standard variant. The reason is the high environmental cost of copper, used in electric cables. This high environmental cost results mainly from the impact categories eutrophication and human toxicity (non-cancer effects) (Figure 7.19). Besides the electric and data cables, main contributors are the storm and sanitary sewer, which represent respectively 29% and 21% of the life cycle environmental cost in the standard variant.

The use of polyvinylchloride (PVC) pipes or ribbed polypropylene (PP) pipes has a limited influence on the environmental impact (Figure 7.18), with respectively an increase of 6% and reduction of 4% of the impact of the sewer system (including the storm and sanitary sewer).

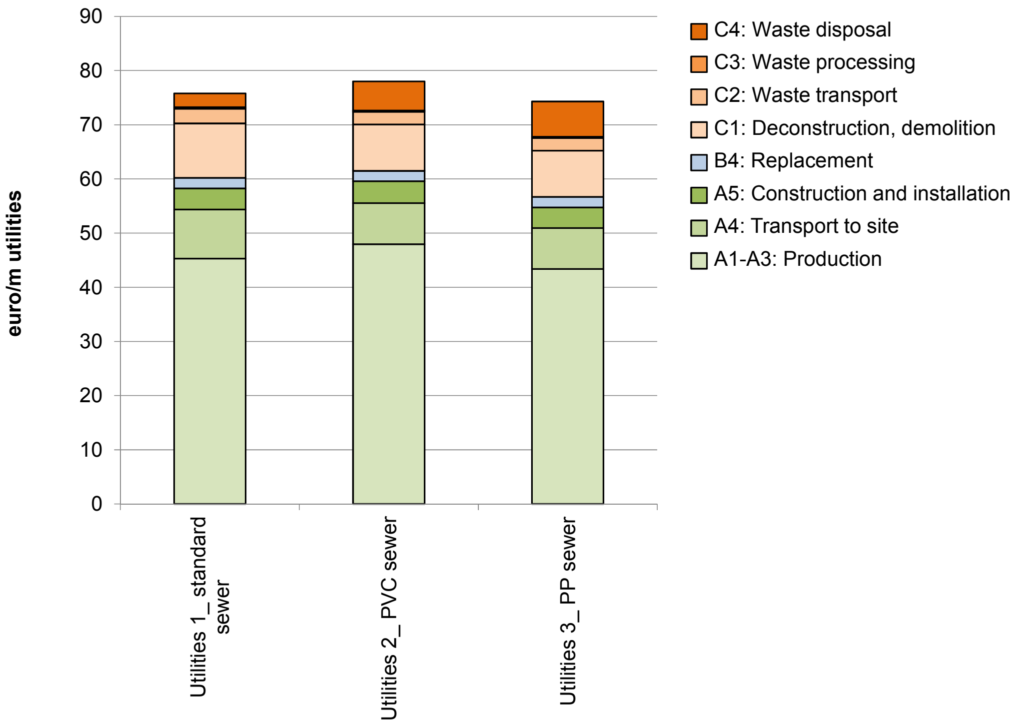

Figure 7.17: Life cycle environmental cost of the variants for utilities, subdivided per life cycle module.

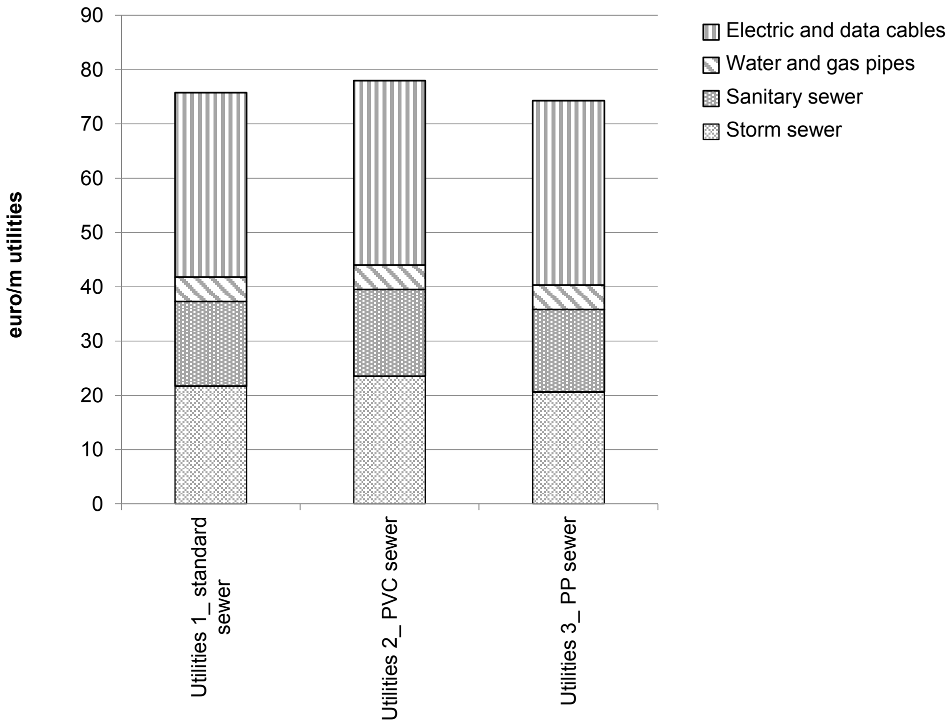

Figure 7.18: Life cycle environmental cost of the variants for utilities, subdivided per work section.

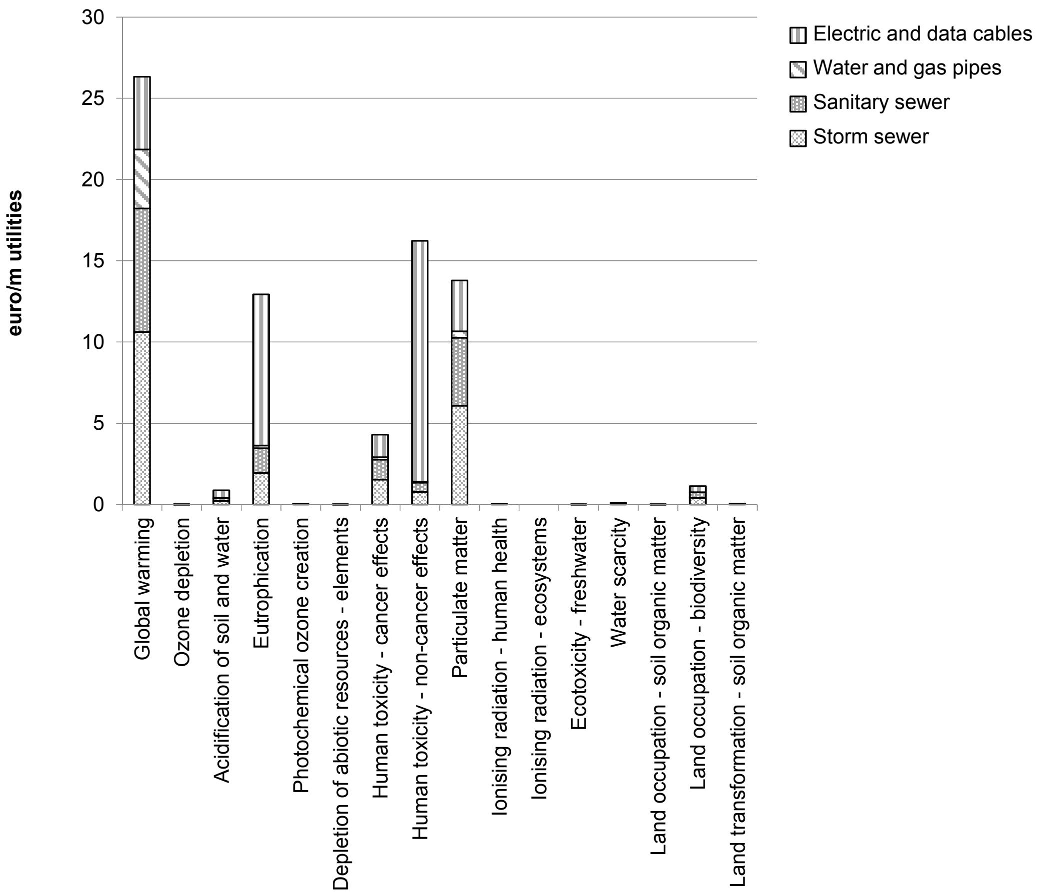

Figure 7.19: Life cycle environmental cost of the standard variant for utilities (Utilities 1_standard sewer), subdivided per impact category and work section.

7.4.4 Financial impact

Similar conclusions as for the environmental cost can be drawn for the financial cost (Figure 7.20). The investment cost is the highest contributor and represents 74% of the life cycle cost in the standard variant. The electricity and data cables have a high financial cost (i.e. 38% of the life cycle financial cost in the standard variant) (Figure 7.21). The alternative types of sewer (PVC or PP pipes) lead to a small change in financial cost of the sewer system, i.e. +2% and -7% respectively.

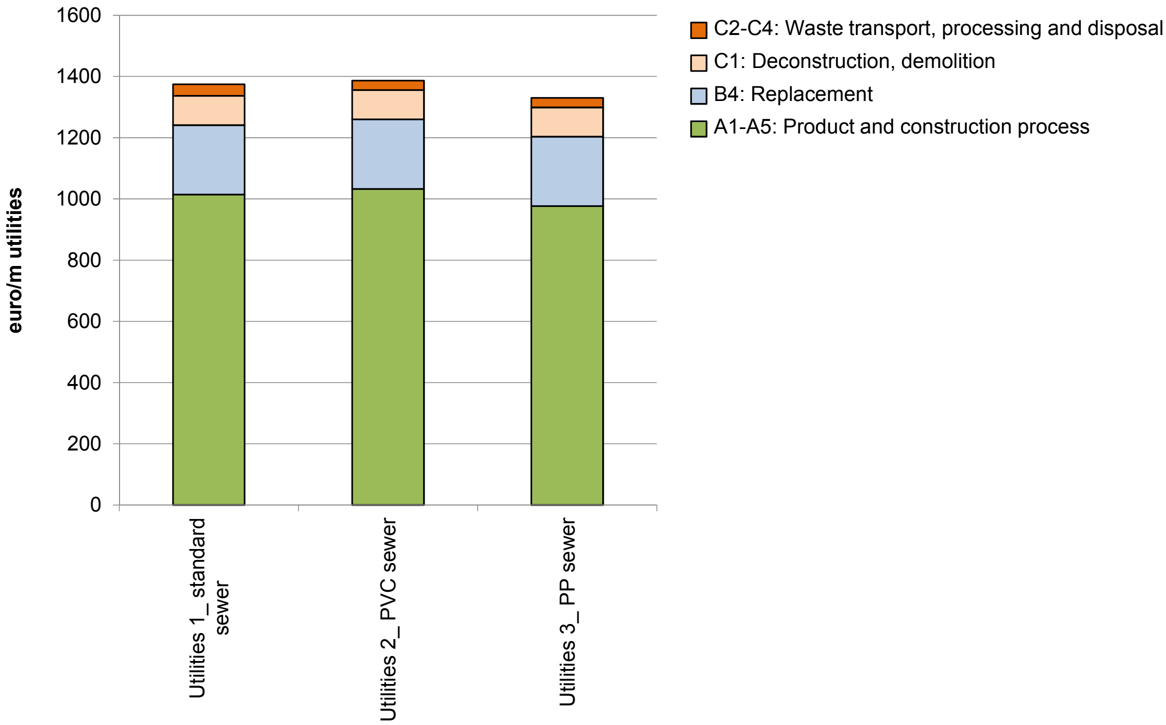

Figure 7.20: Life cycle financial cost of the variants for utilities, subdivided per life cycle module.

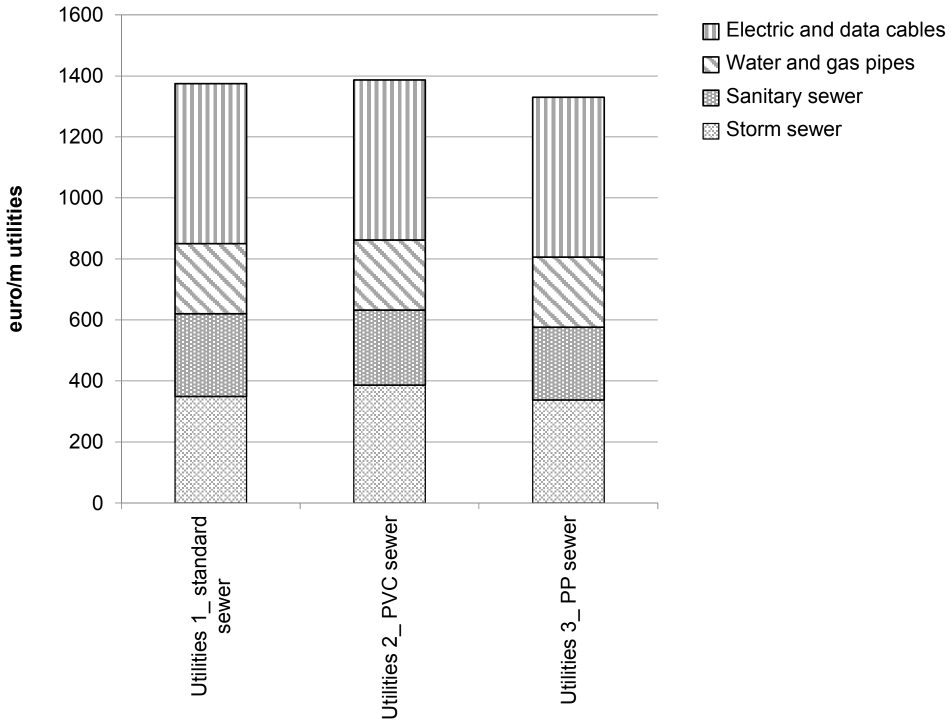

Figure 7.21: Life cycle financial cost of the variants for utilities, subdivided per work section.

7.5 Assessment of open spaces

7.5.1 Description and declared unit

Three variants for the open spaces are analysed (Figure 7.22). The first variant is a square, consisting in a large-scale paved area. Two alternatives are compared, including a standard square accessible for cars and a car-free square. The accessibility of the square for cars has an influence on the composition of the paved area. For the standard square, a similar composition as for the local roads is assumed, including a geotextile, a sub-base, a base and a surface layer (Table 7.1). For the car-free square, lower traffic loads are expected and the same composition as for footpaths is assumed, including a geotextile, a base and a surface layer (Table 7.4). A surface layer in concrete paving stones is assumed in both cases. Concerning the drainage of the paved area, the square is subdivided in modules of 300 m² (20 x 15 m), which are connected via gullies and pipes to the street storm sewer. The sewer layout is indicated with dotted lines in Figure 7.22.

The second and third variants are green areas, including a public park and private gardens. The public park consists of a grass area with trees planted every 15 metres. The private gardens are modelled as a grass area with hedges delimiting the parcels. Small gardens (6 x 18.5 m) as typically are found behind terraced houses, are considered.

Concerning the declared unit, the impact of the open spaces is assessed per square metre. As for the road infrastructure, a life span of 60 years is assumed.

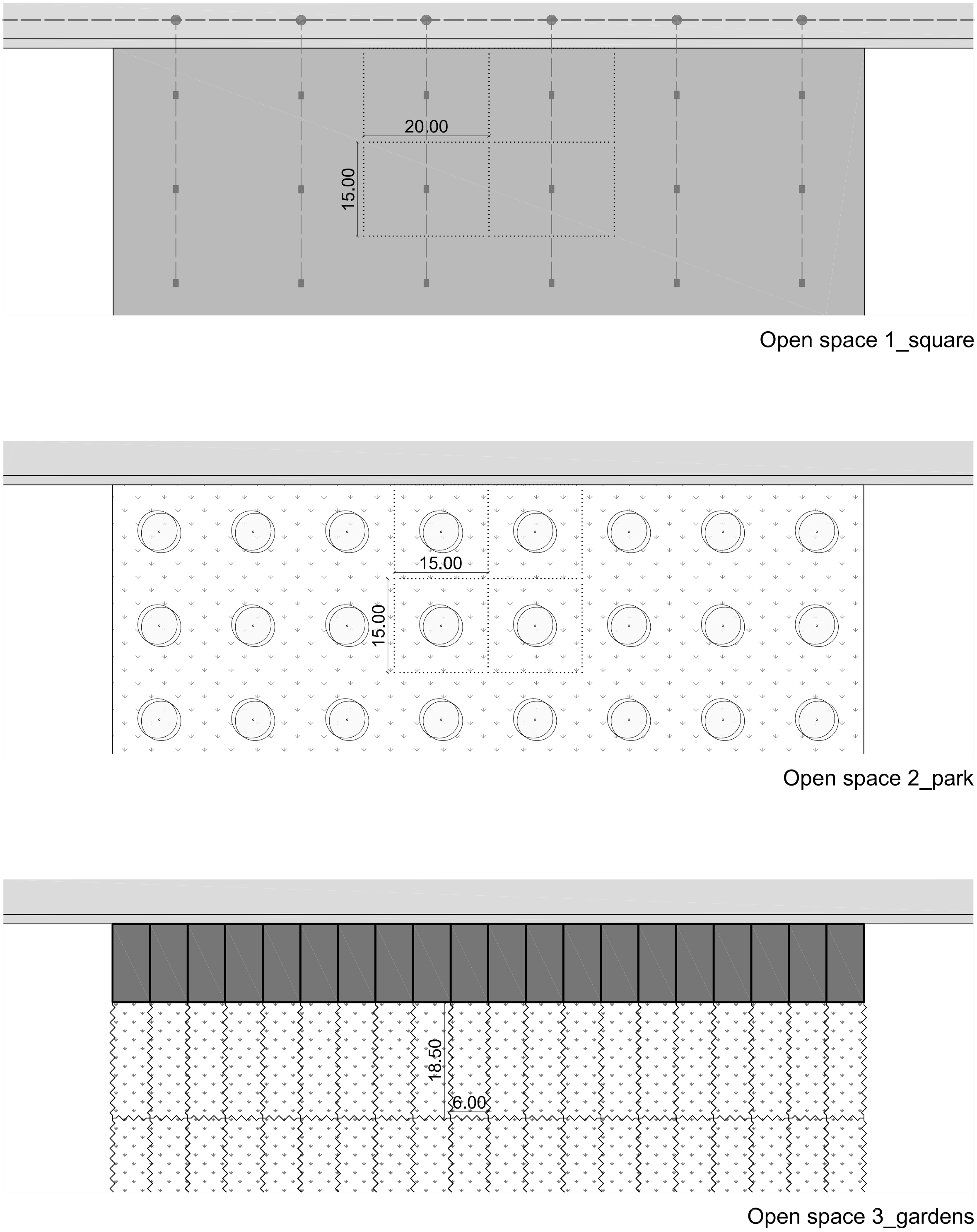

Figure 7.22: Variants for the open spaces.

7.5.2 Life cycle scenarios

Concerning the squares, the same life cycle scenarios as for other paved areas are assumed. An overview of the maintenance and replacement scenarios is provided in Table 7.2 (see section 7.1.2).

Regarding the maintenance of green areas[13], scenarios are defined based on specialised literature (ANB 2006; ANB 2008; Zelkova 2017). The scenarios are reported in Table 7.6. By convention, interventions which occur at least once a year, i.e. grass cutting and the cut and trim of hedges, are defined as cleaning processes (submodule B2.1). Interventions with a lower frequency, such as the prune, trim and cut of trees are defined as maintenance processes (submodules B2.2-B2.3). Replacement of trees and hedges are not considered as their life span is assumed to be longer than 60 years.

Table 7.6: Maintenance scenarios for green areas, based on data from (ANB 2006; ANB 2008; Zelkova 2017)

Work sections	Cleaning	Maintenance
Grass in garden	Grass cutting - 26 times a year	-
Grass in park	Grass cutting - 15 times a year	-
Hedge	Cut and trim - twice a year	-
Tree	-	Prune, trim and cut - 5 years

7.5.3 Environmental impact

The life cycle environmental cost of the open spaces is shown in Figure 7.23. Small environmental cost differences are found between the standard square and the car-free square as the sub-base, which is not required in the car-free variant, has only a limited environmental impact. The life cycle environmental cost of the car-free square is hence only 9% lower compared to the standard variant.

The environmental impact of the green areas is not assessed due to a lack of data regarding the cultivation of trees and plants in Ecoinvent version 2.2[14]. As a consequence, only the primary land use impacts will be considered when assessing the environmental impact of the green areas in the schematic neighbourhood models (see Chapter 8).

[13] The use of fertilisers and weed killers for the maintenance of green areas is not included in the analysis but could have a high environmental and financial impact, especially in private gardens.

[14] The impact data related to plant production are much more extended in the more recent versions of Ecoinvent (version 3) (Ecoinvent centre 2017). It will therefore be possible to include the impact of the cultivation of trees and plants in the future update of the assessment method.

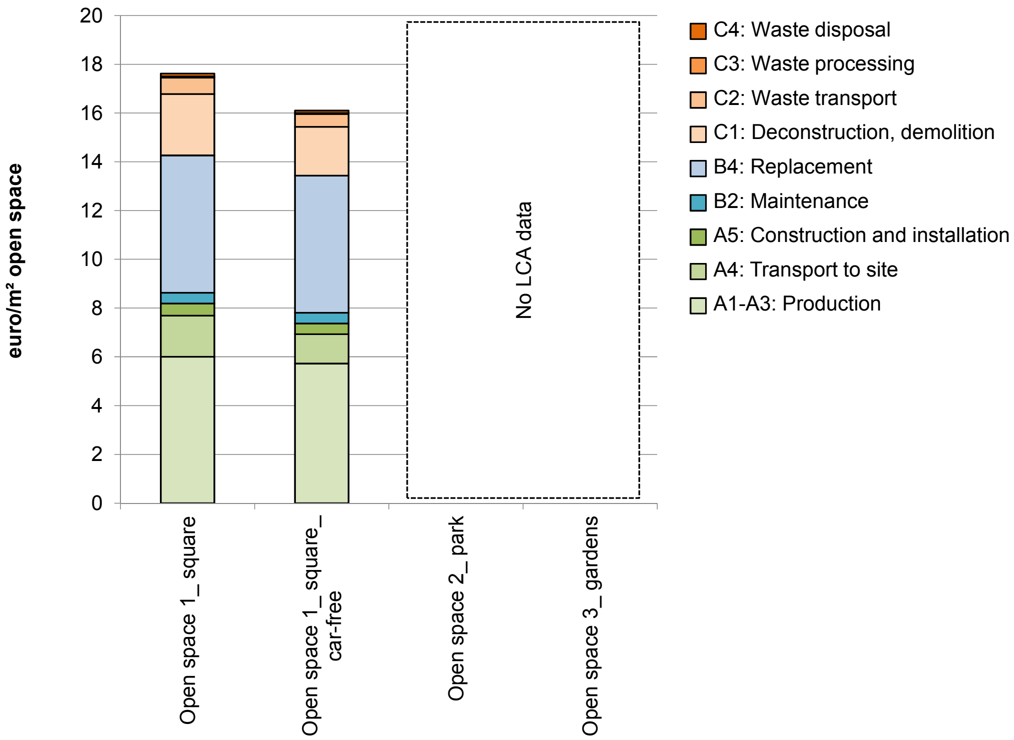

Figure 7.23: Life cycle environmental cost of the open space variants, subdivided per life cycle module.

7.5.4 Financial impact

The life cycle financial cost of the open spaces is shown in Figure 7.24. As for the environmental impact assessment, small cost differences are found between the standard square and the car-free square. The life cycle financial cost of the car-free square is only 6% lower compared to the standard variant, due to the limited cost reduction resulting from the absence of the sub-base.

Cleaning processes have a high influence on the results of the green areas with a contribution of more than 95% to the life cycle financial cost. Significant variations are moreover noticed depending on the type of green area. The life cycle financial cost of the private gardens is more than 10 times higher compared to the park variant. The reason is the higher frequency of grass cutting (26 times instead of 15 times a year) and the high cost for cutting and trimming the hedges in gardens. Regarding the cost allocation, it should be noted that the cost for parks is a public cost, carried by municipalities, while the cost for gardens is a private cost for the neighbourhood inhabitants. It was moreover assumed that all green areas are maintained by professional gardeners[15] while, in practice, gardens are often maintained by the inhabitants, which considerably reduces the related maintenance cost.

[15] Self-build, cleaning and maintenance by the neighbourhood inhabitants are not considered in this research (see Chapter 3).

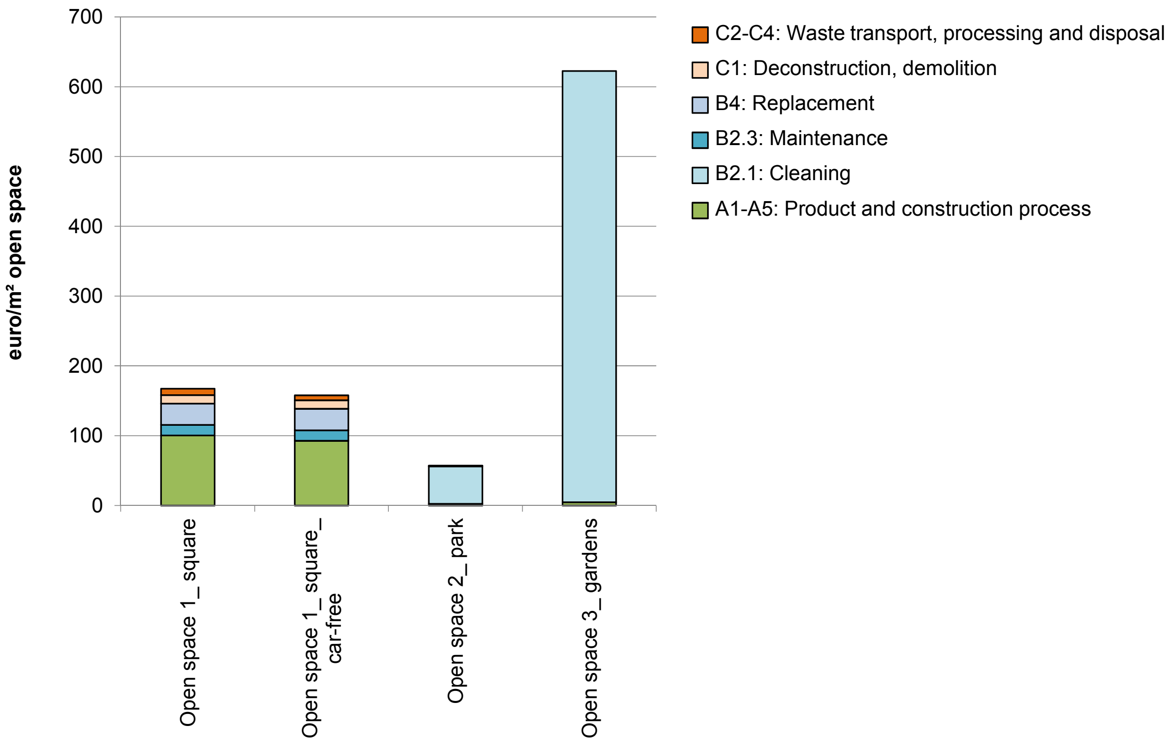

Figure 7.24: Life cycle financial cost of the open space variants, subdivided per life cycle module.

7.6 Assessment of parking facilities

7.6.1 Description and declared unit

Various types of parking facilities can be provided to satisfy the residents' parking needs in neighbourhoods. Three variants are analysed (Figure 7.25). The first variant focuses on individual parking drives, in front of each housing unit. In the second variant, street parking is considered, consisting in parking strips parallel to the traffic direction. The third variant is a collective parking lot with a capacity of 48 parking spaces[16]. In contrast to the other variants, drainage of the parking lot is required to collect the rainwater from the large paved area. The sewer layout is indicated with dotted lines in Figure 7.25.

Concerning the composition of the paved areas, the same composition as for the local roads is considered, including a geotextile, a sub-base, a base and a surface layer (Table 7.1). For the analysis, a surface layer in asphalt is assumed. Furthermore, the boundaries between adjacent parking spaces in variant 2 and 3 are marked with white solvent paint.

Regarding the declared unit, the impact of the parking facilities is assessed per provided parking space to allow for a meaningful comparison between the different variants. As for the road infrastructure, a life span of 60 years is assumed.

[16] The parking capacity is defined based on the parking needs of the medium-rise apartment building analysed in Chapter 8 and consisting of 48 dwellings.

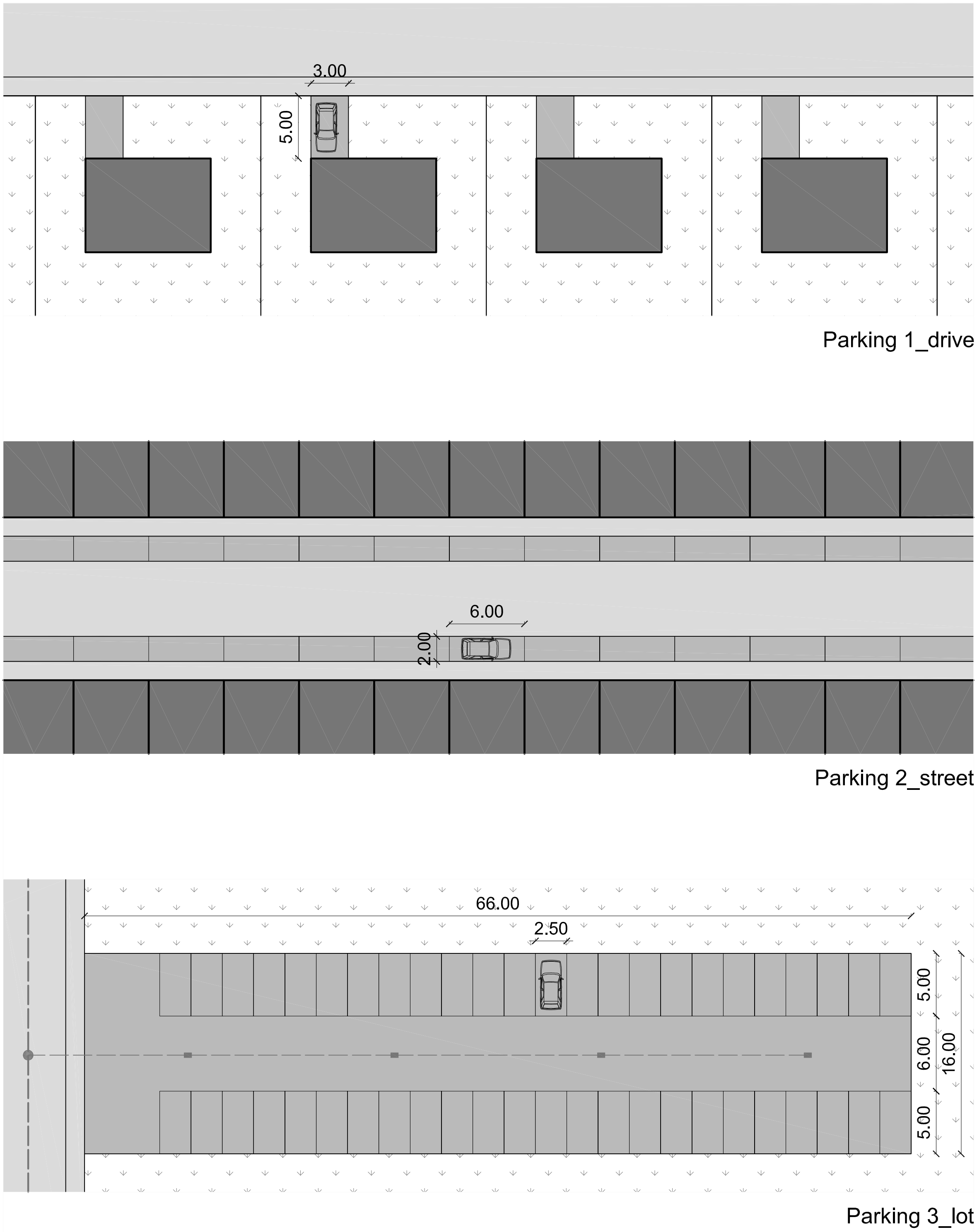

Figure 7.25: Variants for the parking facilities.

7.6.2 Life cycle scenarios

The same life cycle scenarios as for the roads are used for the parking facilities. An overview of the maintenance and replacement scenarios is provided in Table 7.2 (see section 7.1.2).

7.6.3 Environmental impact

The life cycle environmental cost is shown in Figure 7.26. The lowest life cycle environmental impact is obtained for the street parking variant as this variant requires the smallest paved area per parking space. Compared to the parking drive variant, this results in an impact reduction of 16%. The life cycle environmental impact of the third variant (parking lot) is much higher, i.e. 50% higher compared to the parking drive variant. This high impact results from the circulation area between the parking spaces and the additional drainage and line marking required in collective parking lots.

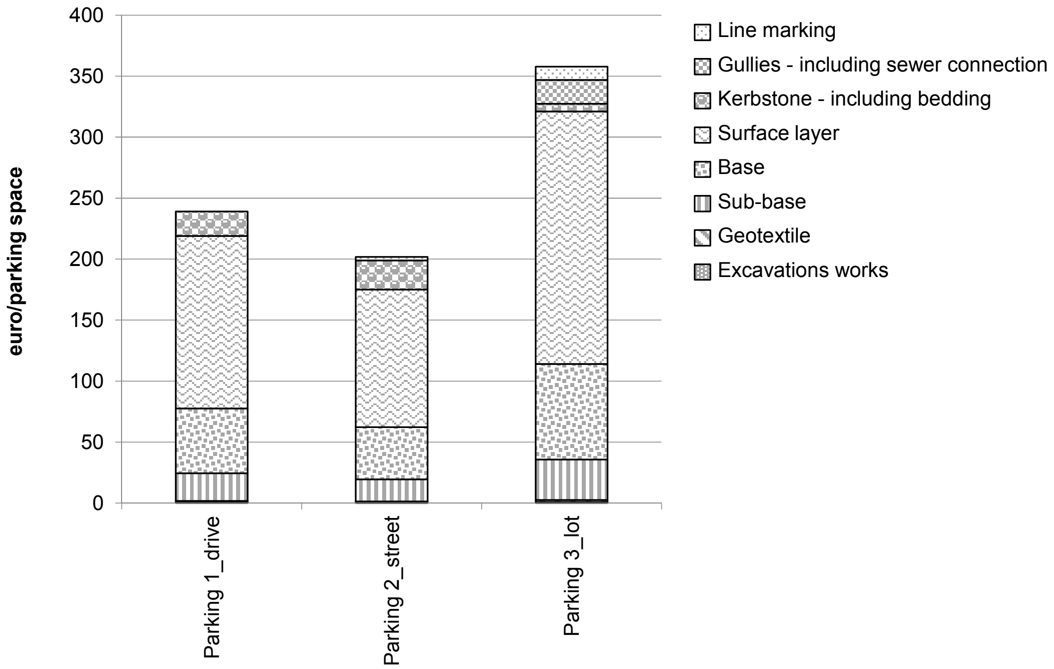

Figure 7.26: Life cycle environmental cost of the parking facilities, subdivided per work section.

7.6.4 Financial impact

Similar conclusions as for the environmental cost can be drawn for the financial impact (Figure 7.27). The lowest life cycle financial cost is obtained for the street parking variant (-18% compared to the parking drive variant). The parking lot variant has a much higher life cycle financial impact, i.e. 43% higher compared to the parking drive variant.

Regarding the cost allocation, it should be noted that the first and third variant are private parking facilities while street parking is a public facility, which cost is carried by municipalities. However, cost for street parking is indirectly assigned to users or inhabitants, as municipalities often apply parking space levies.

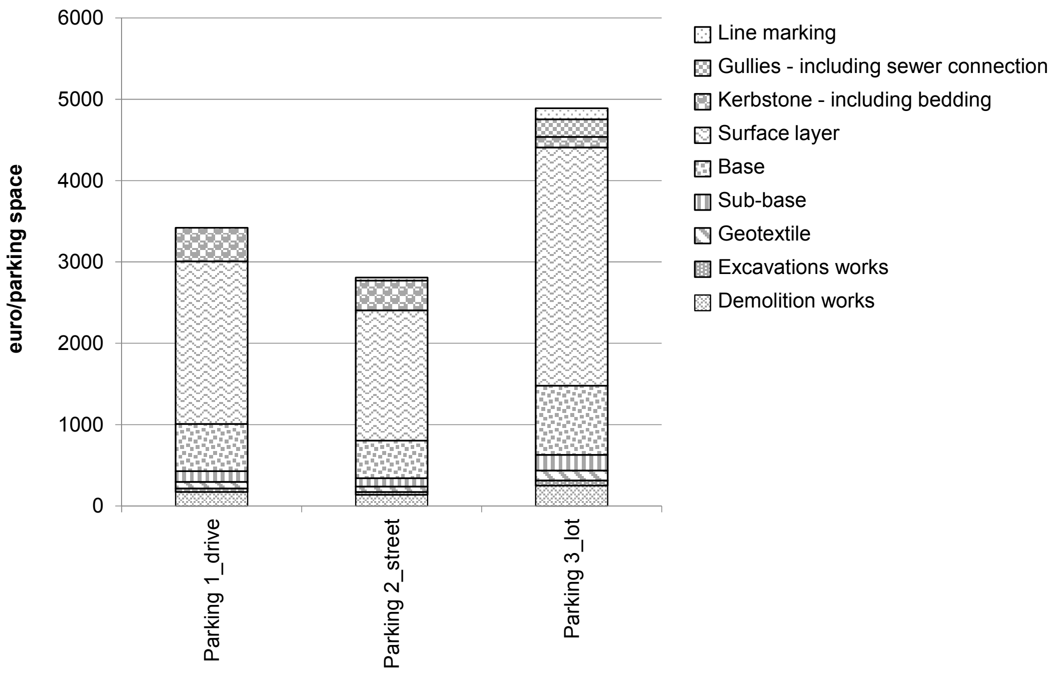

Figure 7.27: Life cycle financial cost of the parking facility variants, subdivided per work section.

7.7 Conclusions

In this chapter the financial and environmental impact of networks and open spaces are assessed, using the integrated life cycle approach. Based on this analysis, a number of conclusions can be formulated for respectively the paved surfaces (i.e. roads, bicycle paths, footpaths, squares and parking facilities), green areas and utilities.

First, the environmental impact assessment of the paved areas shows the importance of the production phase, with a contribution of about 25 to 40% to the life cycle environmental cost, depending on the analysed element. The high influence of the production phase was also concluded by other researchers focussing on the impact of road infrastructure (Mroueh et al. 2001; Weiland 2008; Gschösser 2011). Other main contributors to the life cycle environmental cost are the energy use for road lighting, and replacement of work sections.

Among the work sections, the surface layer causes a high impact with a contribution of about 30-40% to the life cycle environmental cost of roads and 55-75% for the other paved areas analysed. Therefore the selection of environmental friendly surfacing materials and the optimisation of their maintenance and replacement scenarios are important parameters to reduce the environmental impact of paved areas. The significant role of the maintenance and replacement processes was also pointed out in (Gschösser 2011; Giustozzi et al. 2012; Jullien et al. 2014). As was found in the analysis of the bicycle paths, another significant contributor to the environmental impact is road paint or coating due to the high replacement frequency. For large coloured surfaces, the use of pigmented surface layers should therefore be preferred above the use of road paint or coating.

As mentioned in the literature (Häkkinen and Mäkelä 1996; Weiland 2008; Gschösser 2011), preferences between pavement types are influenced by the environmental impact indicators considered. Therefore the use of an aggregated indicator, such as the environmental cost, is recommended to support decision taking. However, the results for the paved areas analysed in this research stress the importance of the selected monetary values. In the current MMG method, the results are mainly influenced by the global warming indicator which is highly valued compared to other impact categories. Further research on the monetary values is therefore required as the uncertainties are still high (De Nocker and Debacker 2015).

Similar conclusions can be drawn for the life cycle financial cost of the paved areas. The investment is the main contributor, i.e. about 50-65% of the life cycle financial costs, followed by the replacement of work sections. Among the work sections, the surface layer causes a high cost, i.e. about 30-40% of the life cycle financial cost for the roads and about 55-65% for the other paved areas analysed. Despite these similarities, it is identified that preferences between the surface layers based on the financial cost differ importantly from those based on the environmental cost. For example, the reclaimed cobblestone pavement causes the highest financial cost but the lowest environmental cost.

Second, for the green areas, no environmental impact assessment was done due to lack of data in Ecoinvent version 2.2. Although the impact of the cultivation of trees and plants is expected to be limited, further research is recommended to integrate these in future. On the contrary, the life cycle financial impact of green areas was assessed. Specific for the green areas is the high contribution of cleaning processes, such as grass cutting and the trim and cut of hedges, which represents more than 95% of the life cycle financial cost. The frequency of these processes, which can vary a lot depending on the type of green area, is therefore a major factor of influence for their financial impact.

Third, concerning the utilities, the life cycle environmental impact is of the same order of magnitude as the impact of roads (about 80€/m for the utilities and 100-120 €/m for the local roads, excluding the energy use for road lighting). The impact of the utilities should therefore be included when assessing the impact of neighbourhood networks. As for the paved areas, the production phase is the highest contributor and represents about 60% of the life cycle environmental cost. Among the work sections, the high environmental cost of the electric cables was highlighted, with a contribution of about 45% to the life cycle environmental cost of utilities.

Similar conclusions are drawn for the financial impact of utilities. The life cycle financial cost is of the same order of magnitude as the cost of the roads (about 1400 €/m for the utilities and about 1500€/m for the roads excluding the energy use for road lighting). The investment is also the main contributor (about 75% of the life cycle financial cost). Among the work sections, the electric cables have a high financial cost, with a contribution of about 40% to the life cycle financial cost.

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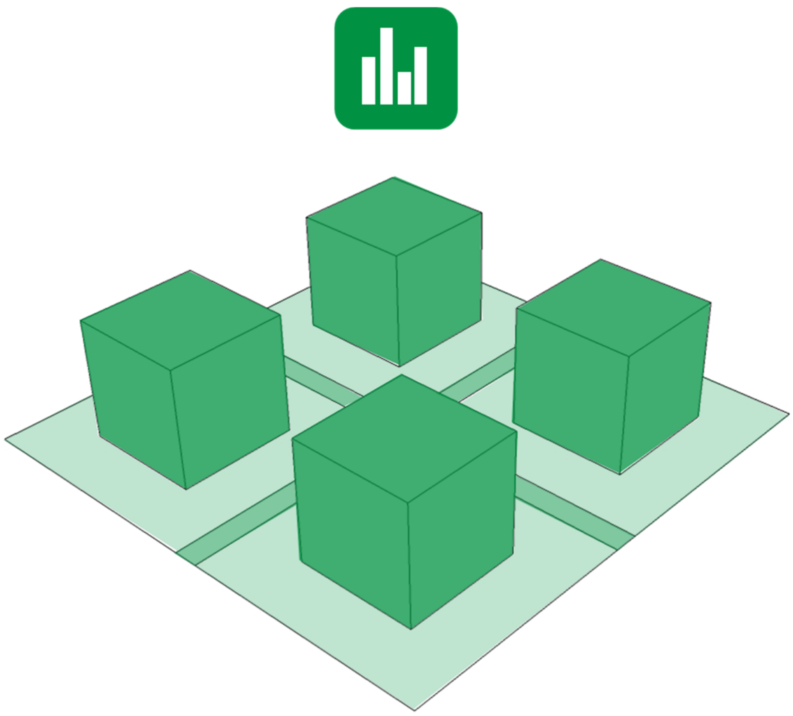
CHAPTER 8

Assessment of schematic neighbourhood models

This chapter focuses on the assessment of schematic neighbourhood models with various built densities. The objective is to investigate the influence of urban planning on the financial and environmental impacts of neighbourhoods. Two reference variants representative for existing and newly built neighbourhoods are analysed from an overall perspective. This is followed by a detailed assessment of following five aspects: material use, operational energy use, operational water use, primary land use and user transport. For each of these aspects, a number of sustainability measures are assessed, which will be used for the comparison with the scoring tools in Chapter 9.



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8.1 Introduction

This chapter aims at assessing the effect of urban planning on the sustainability of neighbourhoods, which corresponds to the second research question addressed in this PhD dissertation. Four schematic neighbourhood models with various layouts and built densities, ranging from detached houses to apartment buildings, are analysed. For each of the four models, two reference variants, representative for existing and newly built neighbourhoods (see section 8.3), have been defined to analyse the influence of the construction standards and technologies. A more extended analysis of neighbourhood layouts and technical solutions is not included in this research as the purpose it to illustrate the potential of the developed approach and not to carry out a detailed study of the Belgian building stock.

The existing and newly built variants of the four models are analysed from an overall perspective to gain insight in the main trends and impact contributors. This is followed by a detailed assessment of the main impact drivers, i.e. material use[1], operational energy use, operational water use, primary land use and user transport (section 8.4 to 8.8). The detailed analysis aims at providing deeper insight in all impact contributors. The impact assessment results will furthermore be used for the comparison with the scoring tools in Chapter 9. To allow for this comparison, the impact of a number of sustainability measures (i.e. strategies) are assessed for each of the impact drivers. The sustainability measures are selected based on the literature review of scoring tools for neighbourhoods (see Chapter 2) and frequently implemented strategies in current practice. By convention, the measures are defined compared to the reference variant for newly built neighbourhoods, as some measures are only meaningful in the context of the new construction standards. For example, a heat pump is only relevant in an insulated building with a low temperature heating system. Furthermore, the strategies include both higher and lower standards compared to the reference situation to investigate the sustainability of current building standards and regulations.

8.2 Description of the neighbourhood models

The four schematic neighbourhood models consist of respectively detached houses (Model 1), semi-detached houses (Model 2), terraced houses (Model 3) and apartments (Model 4). A real neighbourhood case study, including a mix of building typologies, is not considered in this research as the objective is to investigate the influence of the neighbourhood layout and built density based on clearly distinctive models.

The neighbourhood models are inspired by representative neighbourhoods located in the Belgian municipality of Leuven. These neighbourhoods are only selected for their representativeness for the Belgian context and do not aim to be sustainable and/or innovative. The schematic models are defined using the bottom-up approach of (Berghauser

[1] Material use refers to the life cycle impacts of the construction products, excluding the following life cycle modules: A0.3 (land purchase and transformation), B6 (operational energy use), B7 (operational water use), B8 (land occupation) and B9 (user transport) (see Chapter 3).

Pont and Haupt 2010) described in Chapter 4 (Figure 8.1). In a first step, a schematic building lot is defined, consisting of a building, garden and required parking facility. The building is abstracted to a rectangular volume, composed of one or more housing units. All the housing units have a floor area of 150 m². This assumption is based on statistics for newly-built residential buildings in Flanders for the year 2013 (VEA 2016)[2]. Four inhabitants per housing unit are assumed which corresponds to a floor area of 37.5 m²/inhabitant[3]. Furthermore, an orientation of the front and rear façade towards the north and the south is considered in all analysed models. This parameter is important for the heating energy demand calculations.

Urban islands are then defined by combining a number of identical lots. For each island, the surrounding network of streets is composed of a 5 metres wide road with a 1.5 metres wide footpath on both sides. Finally, a neighbourhood is defined by combining a number of urban islands[4] around a central public space. In this research, neighbourhoods of approximatively 400 dwellings are considered. An area of about 10 m² public space/inhabitant is provided in each neighbourhood model.

In the subsequent sections (sections 8.2.1 to 8.2.4), the four neighbourhood models are described, including the representative neighbourhoods and the derived schematic models. In section 8.2.5, an overview is given of the main characteristics of the neighbourhood models.

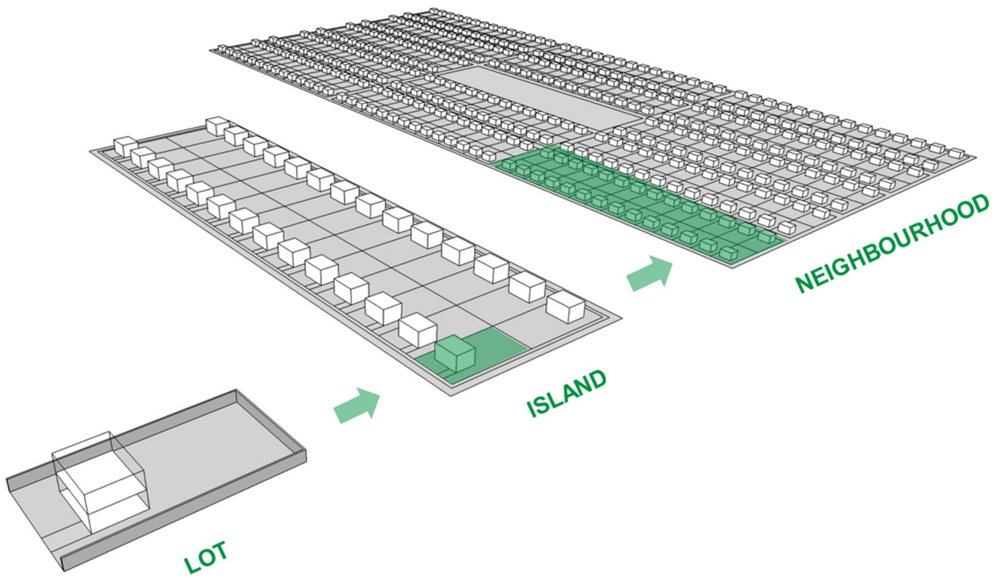

Figure 8.1: Bottom-up approach to define schematic neighbourhood models, based on (Berghauser Pont and Haupt 2010).

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[2] High variations in floor area are noticed depending on the building typology. The average floor area of single-family houses is much higher than of apartments. In this research no variation in floor area is considered as the focus of the analysis is on the impact of the built density.

[3] This assumption is in line with the default value of 35 m²/inhabitant used in the Belgian version of the PHPP software (PIXII 2017)

[4] In contrast to the bottom-up approach of (Berghauser Pont and Haupt 2010), the level of the "fabric" is not considered as the analysed neighbourhoods are composed of only one type of urban island.

8.2.1 Neighbourhood model 1: detached houses

Representative neighbourhood model

Detached houses represent 28% of the Belgian dwelling stock (Belgian Federal Government 2017) and are a widespread building typology, especially in rural areas and city suburbs. The selected representative neighbourhood is located in Heverlee, outside the inner ring of Leuven (Figure 8.2 and Figure 8.3).

Figure 8.2: Aerial view of representative neighbourhood 1 (Google 2017). The urban island used for the definition of the schematic neighbourhood model is indicated by dotted lines.

Figure 8.3: Plan of representative neighbourhood 1 (Flemish Government 2017a). The aggregation levels from lot to urban island are indicated in green.

Schematic neighbourhood model

The schematic model is shown in Figure 8.4 and Figure 8.5. The model is composed of building lots of 18.5 m wide and 33 m deep (6.1 ares). The housing units are 10 m wide, 7.5 m deep and 6 m high. The total floor area of 150 m² is spread over two floors. A parking space for one car is provided in front of each house. The gardens consist of a grass area with hedges delimiting the boundaries of each lot.

Urban islands are defined by combining 28 similar lots. The neighbourhood model is composed of 14 urban islands which are organized around a central public square. The model has a low built density with a Floor Space Index (FSI)[5] of 0.2 and results in a high amount of infrastructure with a Network Floor Index (NFI)[6] of 0.086.

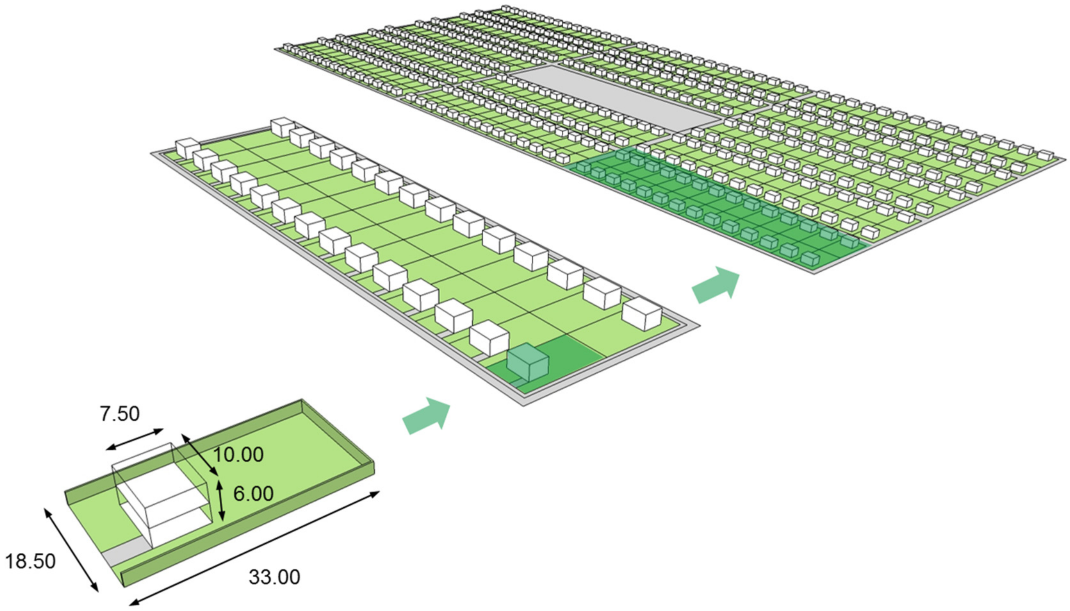

Figure 8.4: Definition of schematic neighbourhood model 1 (from lot, island, to neighbourhood).

[5] The Floor Space Index is calculated as the ratio of the gross floor area to the base land area (see Chapter 4).

[6] The Network Floor Index (NFI) is calculated as the ratio of the network length to the gross floor area (see Chapter 4)

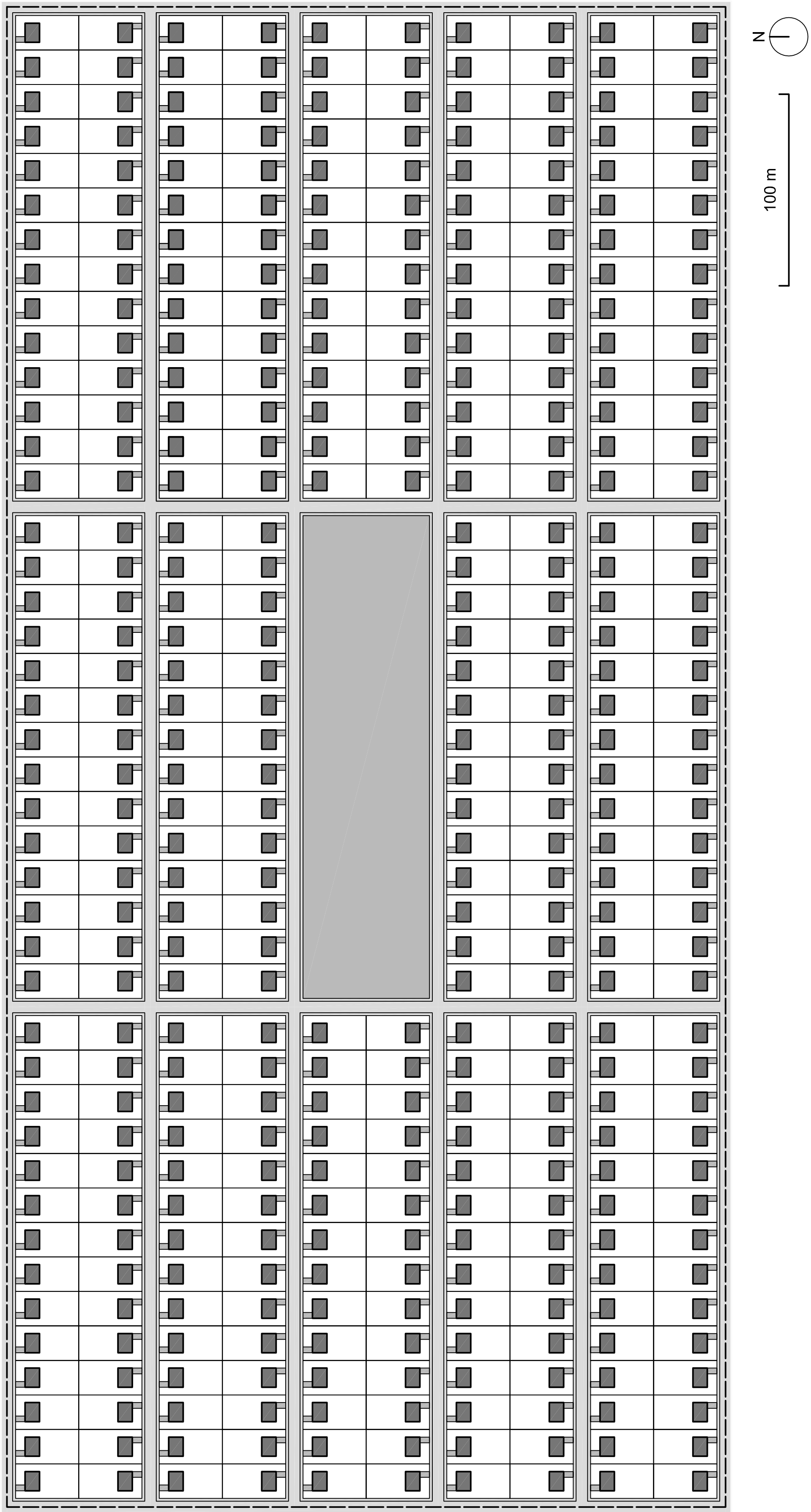

Figure 8.5: Plan of schematic neighbourhood model 1.

8.2.2 Neighbourhood model 2: semi-detached houses

Representative neighbourhood model

The second model consists of semi-detached houses which are more compact than detached houses. Semi-detached houses represent 19% of the Belgian dwelling stock (Belgian Federal Government 2017). The selected representative neighbourhood is located in Heverlee, outside the inner ring of Leuven (Figure 8.6 and Figure 8.7).

Figure 8.6: Aerial view of representative neighbourhood 2 (Google 2017). The urban island used for the definition of the schematic neighbourhood model is indicated by dotted lines.

Figure 8.7: Plan of representative neighbourhood 2 (Flemish Government 2017a). The aggregation levels from lot to urban island are indicated in green.

Schematic neighbourhood model

The schematic model (Figure 8.8 and Figure 8.9) is composed of building lots of 12.5 m wide and 25 m deep (3.1 ares). The housing units are 7.5 m wide, 10 m deep and 6 m high and consist of two floors. A parking space for one car is provided in front of each house. The gardens consist of a grass area with hedges delimiting the boundaries of each lot.

The urban islands are composed of 24 semidetached units, each on an equal sized lot. The neighbourhood model consists of 16 urban islands which are organized around a central public square. The model is characterised by an FSI of 0.34 and an NFI of 0.065.

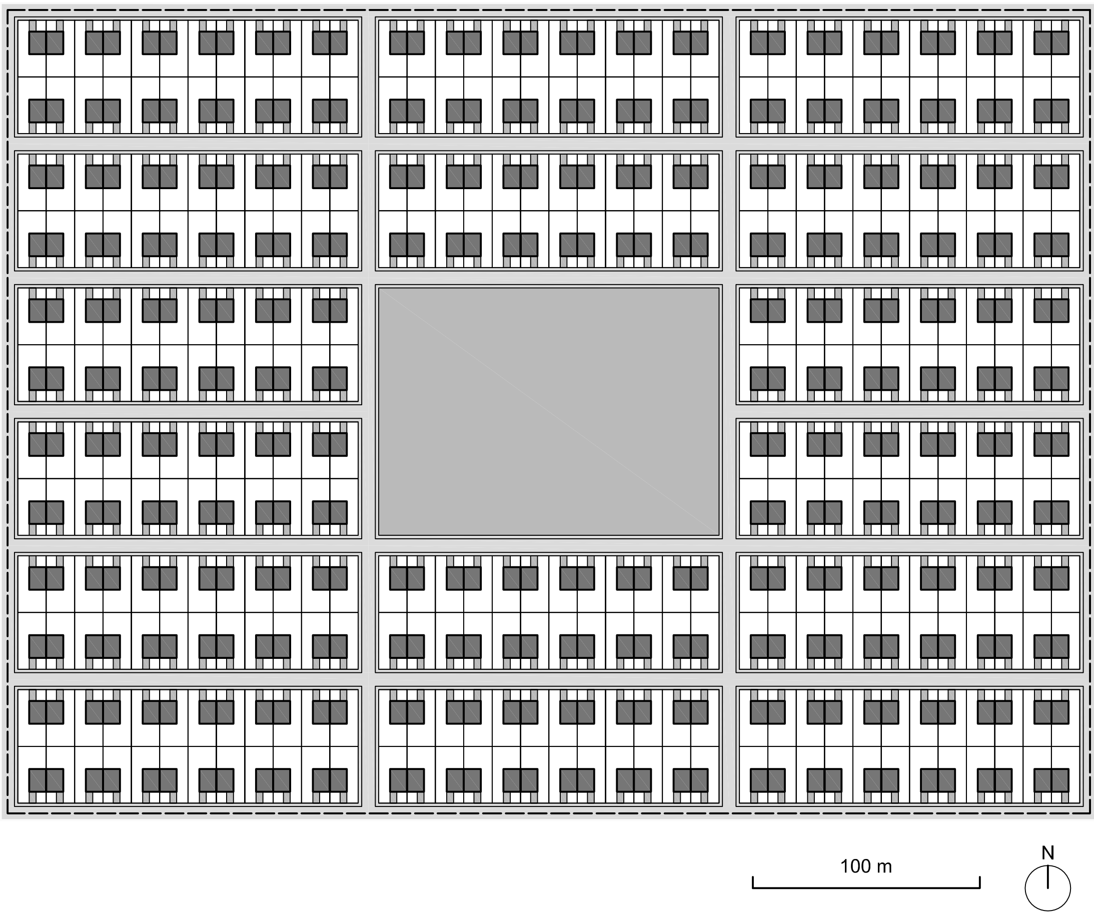

Figure 8.8: Plan of schematic neighbourhood model 2.

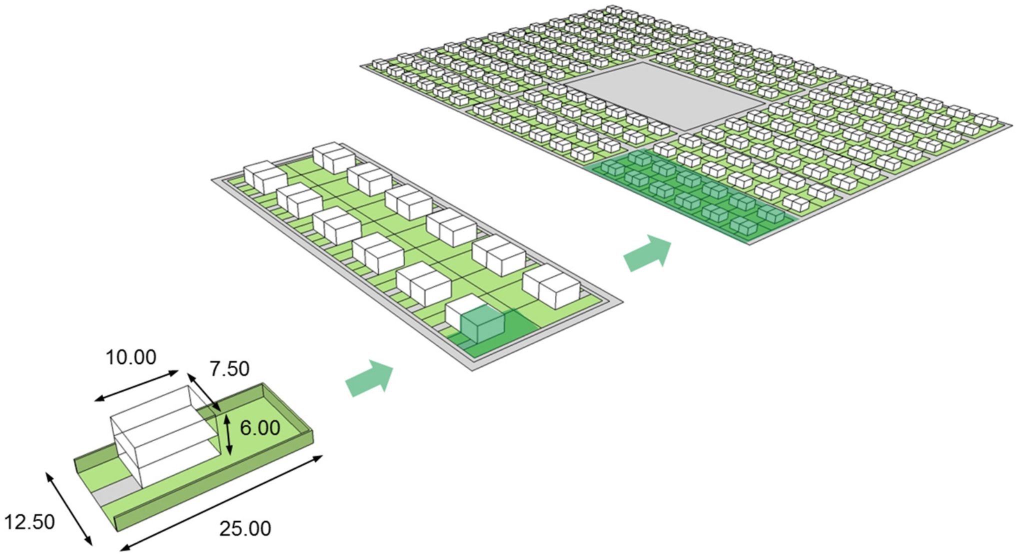

Figure 8.9: Definition of schematic neighbourhood model 2 (from lot, island, to neighbourhood).

8.2.3 Neighbourhood model 3: terraced houses

Representative neighbourhood model

Terraced houses represent 26% of the Belgian dwelling stock (Belgian Federal Government 2017) and are typical for city centres. The selected representative neighbourhood is located in the centre of Leuven, inside the inner ring (Figure 8.10 and Figure 8.11).

Figure 8.10: Aerial view of representative neighbourhood 3 (Google 2017). The urban island used for the definition of the schematic neighbourhood model is indicated by dotted lines.

Figure 8.11: Plan of representative neighbourhood 3 (Flemish Government 2017a). The aggregation levels from lot to urban island are indicated in green.

Schematic neighbourhood model

The schematic model is shown in Figure 8.12 and Figure 8.13. The model is composed of building lots of 6 m wide and 31 m deep (1.9 ares). The housing units are 6 m wide, 12.5 m deep and 6 m high and consist of two floors. The buildings have a small garden consisting of a grass area with hedges. There is no private parking space but parking strips are provided in the street, including exactly one parking space per housing unit.

Urban islands are defined by combining 40 identical lots. The neighbourhood model is composed of 10 urban islands around a central public square. The model is characterised by an FSI of 0.52 and an NFI of 0.039.

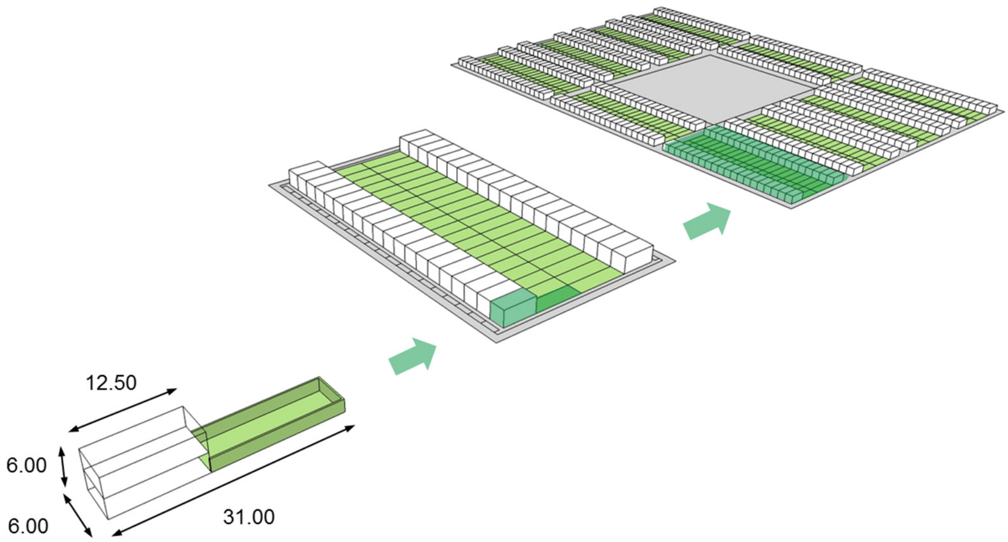

Figure 8.12: Definition of schematic neighbourhood model 3 (from lot, island, to neighbourhood).

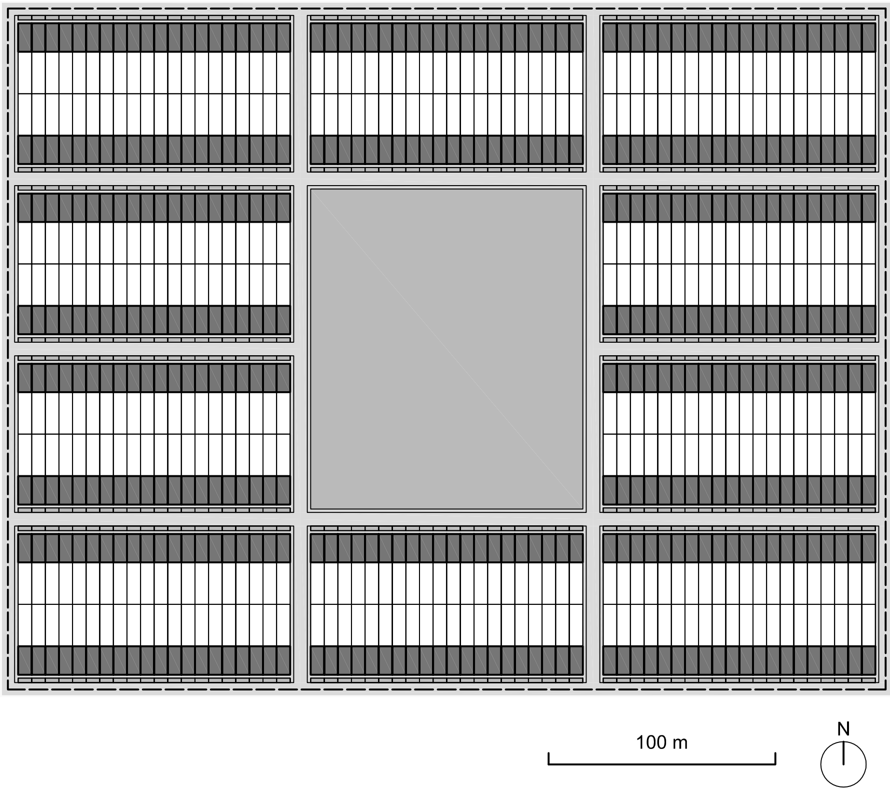

Figure 8.13: Plan of schematic neighbourhood model 3.

8.2.4 Neighbourhood model 4: apartments

Representative neighbourhood model

The last model consists of apartments which represent 26% of the Belgian dwelling stock (Belgian Federal Government 2017). Different building typologies are possible from low-rise to high-rise apartment buildings. In this research, mid-rise apartment buildings are considered. The selected representative neighbourhood is located in Heverlee, outside the inner ring of Leuven (Figure 8.14 and Figure 8.15).

Figure 8.14: Aerial view of representative neighbourhood 4 (Google 2017). The urban island used for the definition of the schematic neighbourhood model is indicated by dotted lines.

Figure 8.15: Plan of representative neighbourhood 4 (Flemish Government 2017a). The aggregation levels from lot to urban island are indicated in green.

Schematic neighbourhood model

The schematic model is shown in Figure 8.16 and Figure 8.17. The model consists of building lots of 81 m by 48 m (38.9 ares). The buildings are 69 m wide, 15 m deep and 24 m high and consist of eight floors. Each building is composed of 48 dwellings which are organized around three circulation cores (including the stairs and elevators). The floor area of the shared circulation spaces is assumed to be 15% of the useful floor area (UFA). As for the other neighbourhood models, the gardens consist of a grass area with hedges delimiting the boundaries of each lot. For each building, a collective parking lot is provided with a capacity of 48 parking spaces (one parking space per housing unit).

Urban islands are defined by combining four similar lots. The neighbourhood model is composed of two urban islands which are organized along a public square. Compared to the other neighbourhood models, this model has the highest built density with an FSI of 1.21. The model generates the lowest amount of infrastructure with an NFI of 0.013.

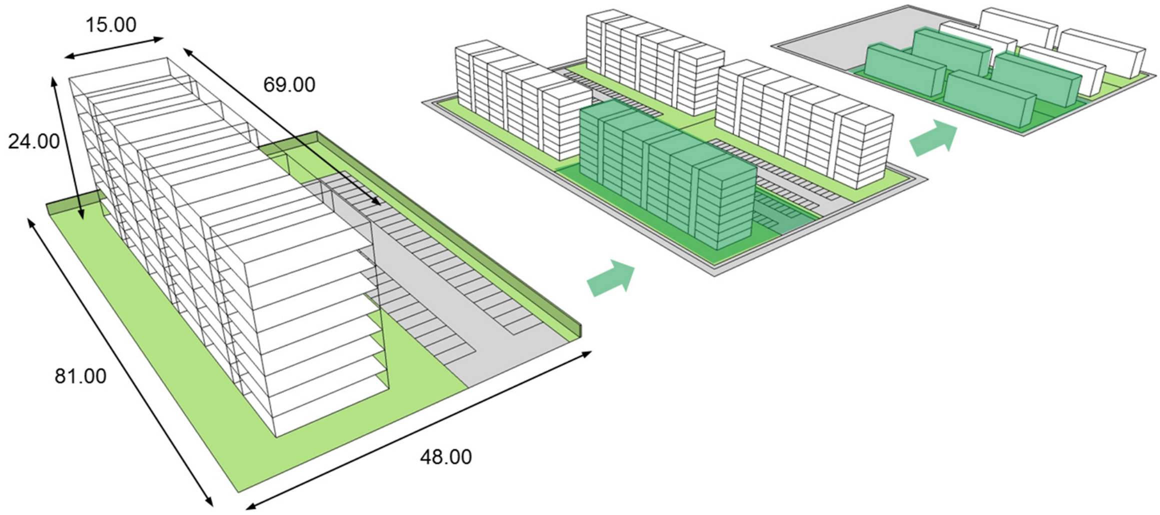

Figure 8.16: Definition of schematic neighbourhood model 4 (from lot, island, to neighbourhood).

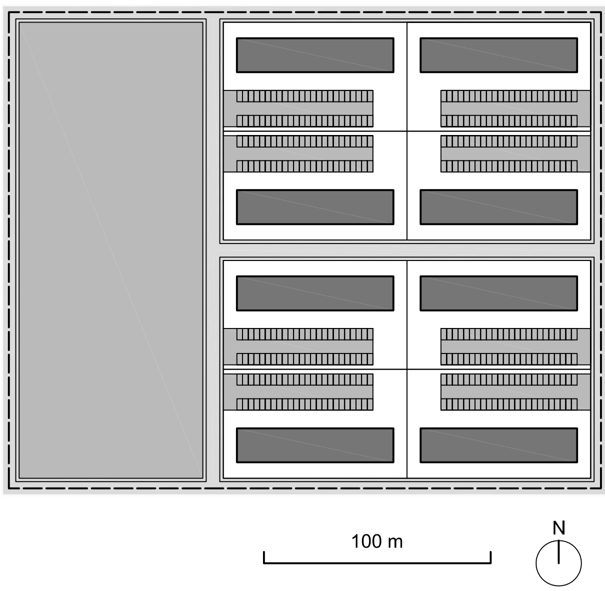

Figure 8.17: Plan of schematic neighbourhood model 4.

8.2.5 Parameters and ratios of the neighbourhood models

For the four schematic neighbourhood models, the main parameters and ratios at the building and neighbourhood level are summarized in Table 8.1 and Table 8.2 respectively.

Table 8.1: Building parameters and ratios of the schematic neighbourhood models.

	Model 1_ detached	Model 2_ semidetached	Model 3_ terraced	Model 4_ apartment
General parameters				
Number of dwellings	1	1	1	48
Number of inhabitants	4	4	4	192 (4)[a]
Total Floor Area TFA (m²)	150	150	150	8280 (172.5)[a]
Floor area circulation spaces (m²)	-	-	-	1080 (22.5)[a]
Useful Floor Area UFA (m²)	150	150	150	7200 (150)[a]
Compactness C	1.25	1.50	2.03	4.07
Ratio elements (unit/m² UFA)				
(13)+ floor on grade (m²)	0.50	0.50	0.50	0.14
(16) foundation (m)	0.33	0.27	0.18	-
(16) foundation party wall (m)	0.00	0.03	0.08	-
(17) pile foundation (m)	-	-	-	0.05
(17) pile foundation party wall (m)	-	-	-	0.02
(21)+ external wall (m²)	1.25	0.85	0.38	0.39
(22.1)+ load-bearing internal wall (m²)[b]	0.51	0.51	0.49	0.64
(22.3)+ non-load-bearing internal wall (m²)[b]	0.51	0.51	0.49	0.64
(22.8)+ party wall (m²)[c]	-	0.20	0.48	0.40
(23)+ storey floor (m²)[d]	0.47	0.47	0.47	-
(23.8)+ party floor (m²)[d]	-	-	-	0.99
(24)+ stairs (p)	0.01	0.01	0.01	0.003
(27.1)+ flat roof (m²)	0.50	0.50	0.50	0.14
(31) windows (m²)	0.15	0.15	0.15	0.17
(32) internal doors (p)	0.10	0.10	0.10	0.12
(5) piped services (m² UFA)	1	1	1	1
(6) electrical services (m² UFA)	1	1	1	1

[a] For a comparison with the single-family houses, the amounts per housing unit are mentioned between brackets.

[b] A distribution of 50% load-bearing and 50% non-load-bearing internal walls is assumed.

[c] For a party wall between two buildings, only half of the party wall is allocated to each building.

[d] The floor openings for stairs are subtracted from the floor area.

Table 8.2: Neighbourhood parameters and ratios of the schematic neighbourhood models.

	Model 1_ detached	Model 2_ semidetached	Model 3_ terraced	Model 4_ apartment
General parameters				
Number of buildings	392	384	400	8
Number of inhabitants	1568	1536	1600	1536
Useful floor area UFA (m²)	58800	57600	60000	57600
Base land area A (m²)	293625	168858	116100	54810
Network length L (m)	5040	3765	2319	852
Gross floor area F (m²)	58800	57600	60000	66240
Built up area B (m²)	29400	28800	30000	8280
Network density N	0.017	0.022	0.020	0.016
Floor Space Index FSI	0.200	0.341	0.517	1.209
Ground Space Index GSI	0.100	0.171	0.258	0.151
Network Floor Index NFI	0.086	0.065	0.039	0.013
Ratio elements (unit/m² UFA)				
Buildings (m² TFA/m²UFA)	1.00	1.00	1.00	1.15
(94.11) road (m)	0.08	0.06	0.04	0.01
(94.13) footpath (m)	0.16	0.12	0.07	0.03
(94.14) parking facilities (parking space)	0.01	0.01	0.01	0.01
(94.15) square (m²)	0.28	0.28	0.28	0.28
(94.22) gardens (m²)	3.36	1.48	0.74	0.25
(95) piped services (m)	0.09	0.07	0.04	0.01
(96) electrical services (m)	0.09	0.07	0.04	0.01
Ratio land use (m²/m² UFA)				
Land use buildings	0.50	0.50	0.50	0.14
Land use road infrastructure	0.75	0.56	0.33	0.13
Land use parking facilities	0.10	0.10	0.08	0.15
Land use square	0.28	0.28	0.28	0.28
Land use gardens	3.36	1.48	0.74	0.25
Total land use	4.99	2.93	1.94	0.95

The main element ratios of the schematic neighbourhood models are represented graphically in Figure 8.18. The influence of the built density and compactness can be clearly identified. Concerning the building elements, more compact buildings, such as terraced houses and apartments, have lower ratios of building envelope elements (i.e. floor on grade, external wall and roof) but higher ratios of internal building elements (i.e. internal wall and floor). Concerning the neighbourhood elements, the ratios of networks and open spaces decrease with the increase of the built density. Only the ratio for the square is similar as an area of about 10 m² public space/inhabitant is provided in each neighbourhood model.

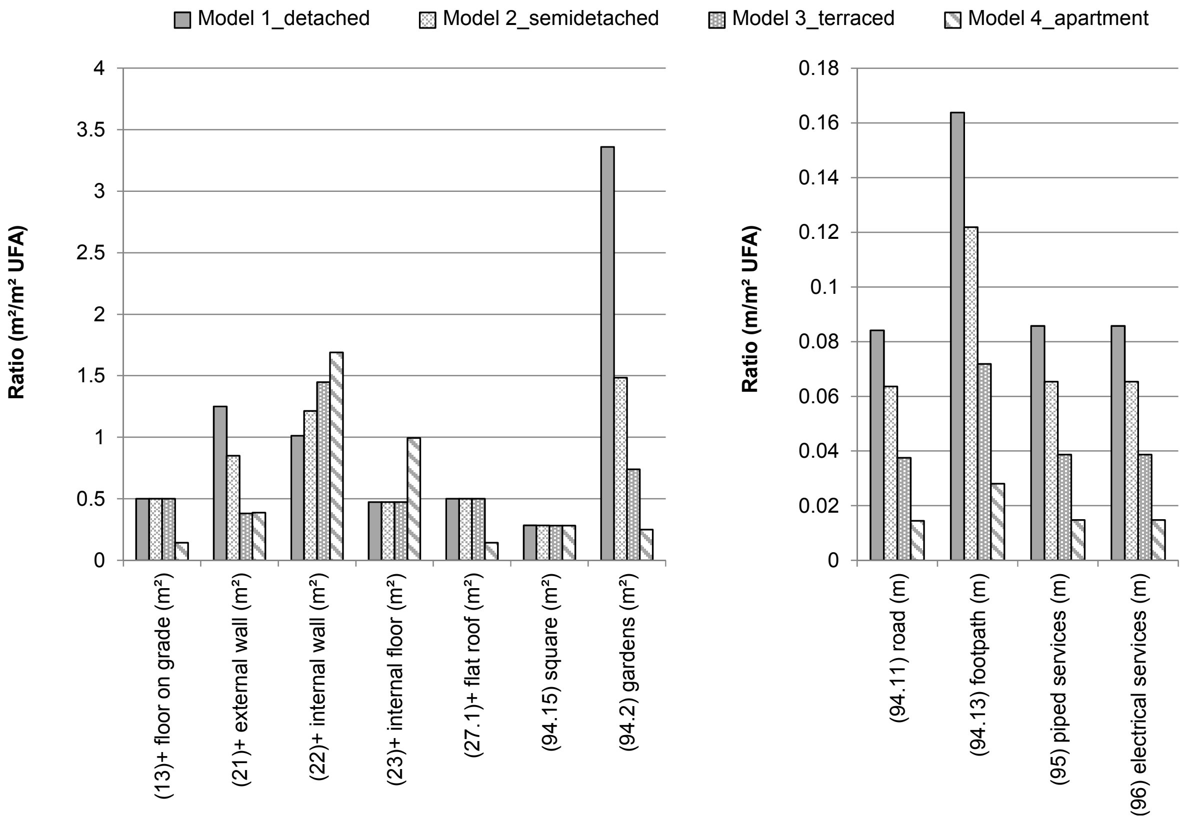

Figure 8.18: Main element ratios of the schematic neighbourhood models.

8.3 Assessment of reference variants

8.3.1 Description and parameters

On top of the described geometry, neighbourhoods furthermore differ based on the technical solutions used for the different elements (including services). For each neighbourhood model two reference variants are defined (Table 8.3). The first variant is representative for existing neighbourhoods built before the 1970s energy crisis while the second is representative for newly built neighbourhoods, in line with current building standards in Belgium (year 2017). Both variants are assumed to be built in reference year 2015 but following the common practice of their respective period. The existing variants are thus not assessed as refurbishment projects but as new construction projects, including all the impacts from the initial construction to the end of life.

The buildings are composed of a solid structure consisting of brick walls, concrete floors and a concrete flat roof. The composition of the building elements for the existing and new neighbourhood variants is summarized in Table 8.4 and Table 8.6 respectively. The composition of the building elements is mainly based on elements in the MMG database (Allacker et al. 2013b). For the foundations, piped and electrical services, elements defined in the SuFiQuaD project are used (Allacker 2010; Allacker et al. 2013a). Apart from the insulation level and implemented services, the material choices in both reference variants are very similar. Variations are due to differences in common practice in the two construction periods, such as for example, the internal floors and roofs consisting of prefab hollow core concrete slabs in the new variant, while in situ concrete is used in the existing variant. Furthermore PVC window frames are used in the new variant instead of wooden frames in the existing variant.

Regarding the external elements, variants analysed in Chapter 7 are selected. For the existing neighbourhoods, a surface layer in concrete is considered for the roads, square and parking facilities while concrete tiles are selected for the footpaths. For the new neighbourhoods, roads and parking facilities consist of an asphalt surface layer, while concrete paving stones are selected for the square and footpaths. The composition of the external elements for the existing and new neighbourhoods are summarized in Table 8.5 and Table 8.7 respectively.

Table 8.3: Neighbourhood parameters for the reference variants.

Parameter	Existing neighbourhood	New neighbourhood
Material use		
Building elements	Solid structure	Solid structure
External elements	Surface layer in concrete (roads, square and parking facilities) and concrete tiles (footpaths)	Surface layer in asphalt (roads and parking facilities) and concrete paving stones (footpaths and square)
Energy use		
Insulation level	No insulation	Maximum U-values EPB 2017
Air infiltration rate	12 $m^3/h.m^2$	6 $m^3/h.m^2$
Ventilation system	Natural ventilation (System A)	Natural supply and mechanical exhaust (System C)
Heating system	- Non-condensing oil boiler - Radiators - manual valves - $\eta_{H,global}$ = 42%	- Condensing gas boiler - Radiators - room thermostat - thermostatic valves - outside temperature sensor - $\eta_{H,global}$ = 92%
Hot water production	- Storage vessel 120l, coupled to space heating - $\eta_{HW,prod}$ = 55%	- Coupled instant boiler - $\eta_{HW,prod}$ = 85%
Renewable energy	-	Photovoltaic panels
Water use		
Rainwater collection	-	Rainwater tanks
Sewer type	Combined sewer	Separate sewer
Infiltration system	-	Drainage ditches
Primary land use		
Original land use	Forest land	Forest land
Neighbourhood land use	Urban discontinuously built	Urban discontinuously built
Building land price	Flemish average (187.79 €/m²)	Flemish average (187.79 €/m²)
User transport		
Reference transport profile	Flemish average	Flemish average
Transport facilities	Average (no correction factor)	Average (no correction factor)

Table 8.4: Building elements of the existing neighbourhood variant.

Building element	Composition	U-value (W/m²K)
(13)+ floor on grade	In situ concrete slab 15 cm – screed mix – fired clay tiles	3.21
(16)+ foundation	In situ concrete foundation	n/a
(17)+ pile foundation	Prefab concrete piles	n/a
(21)+ external wall	Facing brick – hollow brick 14 cm – gypsum plaster – acrylic paint	1.27
(22.1)+ load-bearing internal wall	Acrylic paint – gypsum plaster – hollow brick 14 cm – gypsum plaster – acrylic paint	n/a
(22.3)+ non-load-bearing internal wall	Acrylic paint – gypsum plaster – hollow brick 9 cm – gypsum plaster – acrylic paint	n/a
(22.8)+ party wall	Acrylic paint – gypsum plaster – hollow brick 14 cm – gypsum plaster – acrylic paint	n/a
(23)+ storey floor	Acrylic paint – gypsum plaster – in situ concrete slab 15 cm – screed mix – fired clay tiles	n/a
(23)+ party floor	Acrylic paint – gypsum plaster – in situ concrete slab 15 cm – screed mix – fired clay tiles	n/a
(24)+ stairs	Concrete staircase – metal banister	n/a
(27.1)+ flat roof	Bitumen – concrete slope layer – in situ concrete slab 15 cm – gypsum plaster – acrylic paint	3.16
(31) window	Wooden painted frame – single glazing (g-value = 0.85)	4.51
(32) internal door	MDF frame – plain door	n/a
(5) piped services	Non-condensing oil boiler – column radiators – coupled hot water storage vessel – ventilation type A	n/a
(6) electrical services	Electric cables – (elevators)[7]	n/a

Table 8.5: External elements of the existing neighbourhood variant.

External element	Composition
(94.11) road	Geotextile – crushed gravel sub-base – cement bound crushed gravel base – concrete
(94.13) footpath	Geotextile – cement bound crushed gravel base – concrete tiles
(94.14) parking facilities	Geotextile – crushed gravel sub-base – cement bound crushed gravel base – concrete
(94.15) square	Geotextile – crushed gravel sub-base – cement bound crushed gravel base – concrete
(94.22) gardens	Grass and hedges
(95) piped services	Vitrified clay combined sewer – drinking water pipes (HDPE)
(96) electrical services	Electric and data cables

[7] One elevator per circulation core is provided in the model consisting of apartments.

Table 8.6: Building elements of the newly built neighbourhood variant.

Building element	Composition	U-value (W/m²K)
(13)+ floor on grade	Concrete slab 15 cm – PUR board 9 cm – screed mix – fired clay tiles	0.24
(16)+ foundation	In situ concrete foundation	n/a
(17)+ pile foundation	Prefab concrete piles	n/a
(21)+ external wall	Facing brick – PUR board 8 cm – insulating hollow brick 14 cm – gypsum plaster – acrylic paint	0.23
(22.1)+ load-bearing internal wall	Acrylic paint – gypsum plaster – hollow brick 14 cm – gypsum plaster – acrylic paint	n/a
(22.3)+ non-load-bearing internal wall	Acrylic paint – gypsum plaster – hollow brick 9 cm – gypsum plaster – acrylic paint	n/a
(22.8)+ party wall	Acrylic paint – gypsum plaster – hollow brick 14 cm – stone wool 6 cm – hollow brick 14 cm – gypsum plaster – acrylic paint	n/a
(23)+ storey floor	Acrylic paint – gypsum plaster – hollow core concrete slab 12 cm – pressure layer – screed mix – fired clay tiles	n/a
(23)+ party floor	Acrylic paint – gypsum plaster – hollow core concrete slab 12 cm – pressure layer – rock wool 3 cm – screed mix – fired clay tiles	n/a
(24)+ stairs	Concrete staircase – metal banister	n/a
(27.1)+ flat roof	EPDM – PIR board 10 cm – concrete slope layer – pressure layer – hollow core concrete slab 12 cm – gypsum plaster – acrylic paint	0.24
(31) window	PVC frame with thermal interruption – thermally improved double glazing (g-value = 0.61)	1.44
(32) internal door	MDF frame – plain door	n/a
(5) piped services	Condensing gas boiler – panel radiators – coupled instant hot water production – ventilation type C – rainwater collection	n/a
(6) electrical services	Electric cables – (elevators) – PV panels	n/a

Table 8.7: External elements of the newly built neighbourhood variant.

External element	Composition
(94.11) road	Geotextile – crushed gravel sub-base – cement bound crushed gravel base – asphalt
(94.13) footpath	Geotextile – cement bound crushed gravel base – concrete paving stones
(94.14) parking facilities	Geotextile – crushed gravel sub-base – cement bound crushed gravel base – asphalt
(94.15) square	Geotextile – crushed gravel sub-base – cement bound crushed gravel base – concrete paving stones
(94.22) gardens	Grass and hedges
(95) piped services	Concrete storm sewer and vitrified clay sanitary sewer – drainage ditches – drinking water and gas pipes (HDPE)
(96) electrical services	Electric and data cables

The parameters related to the energy performance differ importantly between both reference variants (Table 8.3). In the existing neighbourhood variant, the building elements are not insulated and single glazed windows are used (Table 8.4). The air infiltration rate equals the default value of the Flemish Energy Performance of Buildings (EPB) regulation (12 $m^3/h.m^2$) (Flemish Government 2017b) and natural ventilation is considered. For space heating, an old technical system is selected, composed of a non-condensing oil boiler[8] and radiators with manual valves, leading to a global heating system efficiency ($\eta_{H,global}$) of 42%[9]. Furthermore, the hot water production consists of a storage vessel, coupled to space heating. The efficiency of the hot water production ($\eta_{HW,prod}$) is 55%.

In the new neighbourhood variant, the buildings are insulated to fulfil the EPB standards of 2017 (Flemish Government 2017c) and thermally improved double glazed windows are used (Table 8.6). An improved air-tightness of 6 $m^3/h.m^2$ and a ventilation system C (natural supply and mechanical exhaust) are assumed. For space heating, a condensing gas boiler combined with radiators is selected. Efficient control mechanisms are implemented, including a room thermostat, thermostatic valves and an outside temperature sensor. This leads to a global heating system efficiency ($\eta_{H,global}$) of 92%. For the hot water production, an instant boiler, coupled to space heating is provided. The efficiency of the hot water production ($\eta_{HW,prod}$) is 85%. To fulfil the EPB requirements regarding the use of renewable energy (Flemish Government 2017c), a photovoltaic (PV) system composed of monocrystalline solar panels is installed on the flat roofs. The solar panels are oriented to the south with an inclination of 25° and minimum spacing distances between rows are applied to minimize shading effects. For the neighbourhood models consisting of single-family houses (detached, semi-detached and terraced), 12 panels of 300 Wp[10] can be installed on the roof of each building, which corresponds to a yearly electricity production of 19 kWh/m^2 UFA. For the neighbourhood model consisting of apartments, 240 panels of 300 Wp can be installed per building, corresponding to a yearly electricity production of 8 kWh/m^2 UFA[11].

Concerning rainwater management, the existing neighbourhood variant includes a combined sewer for both wastewater and rainwater discharge. Meanwhile, the new neighbourhood variant is in line with the current Flemish Urban Planning Regulation on Rainwater Management (Flemish Government 2016) and includes rainwater collection tanks, separate storm and sanitary sewers and drainage ditches for rainwater infiltration and buffering. The dimensioning of the rainwater tanks is based on of the rule of thumb of 50 l/m^2 horizontal roof area, with a minimum of 5000 litres for single-family houses (CIW 2016). For the

[8] In this research only individual heating systems (one system per housing unit) are analysed. Collective heating systems for apartments or district heating are not considered. Although individual oil boilers are not common in apartment buildings, the same technical system is assumed in all neighbourhood models.

[9] The calculation of the global efficiency of the heating system is described in Chapter 5.

[10] The peak power is based on technical data for monocrystalline solar panels available on the Belgian market.

[11] The amount of renewable energy produced by the apartment buildings does not fulfil the minimum EPB requirement of 10 kWh/m^2.year. In order to maintain comparability with the models consisting of single-family houses, no additional measures are however implemented.

neighbourhood models consisting of single-family houses, a rainwater tank of 5000 litres is installed per building. For the model consisting of apartments, three tanks of 20000 litres are provided for each building. The dimensioning of the drainage ditches is based on a minimum infiltration surface of 4 m²/100 m² rainwater capturing area[12] and a minimum buffering volume of 25 l/m² rainwater capturing area (CIW 2016).

Concerning the assessment of primary land use, both reference variants are assumed to be built on forest land. As less than 80% of the total neighbourhood area is considered to be sealed in all four neighbourhood models, the land use type "urban discontinuously built" is selected to characterize the land use of the buildings, road infrastructure and open spaces. For the building land price, the Flemish average is assumed (187.79 euro/m²- excluding taxes).

Finally, the impact of user transport is assessed based on the average transport profile for Flanders. Regarding the transport facilities, an average situation is assumed so that no correction factor is applied on the reference transport profile (see Chapter 5).

8.3.2 Environmental impact

The life cycle environmental cost of the reference neighbourhood variants, over 60 years and expressed in euro per m² UFA, is shown in Figure 8.19. Important environmental cost reductions (up to 60%) are noticed between the existing and new neighbourhood variants. The main reason is the 90% lower impact of operational energy use of the new variants compared the existing ones. This is a result of the stricter energy performance requirements, imposed by the EPB standards.

When analysing the impact of the urban form and built density, large variations can be noticed between the neighbourhood models, especially for the existing neighbourhoods. In that case, the life cycle environmental cost of the model consisting of apartments is 43% lower than the model with detached houses. For the new neighbourhood variants, the variations are more limited: the life cycle environmental cost of the model consisting of apartments is 11% lower than the model consisting of detached houses. The reason is the lower contribution of energy use to the life cycle environmental cost in new neighbourhoods, leading to an increase of the relative contribution of other aspects, such as for example user transport, which are not directly influenced by the built density[13].

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[12] The rainwater capturing area is defined as the sum of the horizontal projected roof surfaces and the impermeable paved areas (i.e. road infrastructure, square and parking facilities). For roof surfaces connected to a rainwater tank, a reduction of 80% of the capturing area is assumed, corresponding to the fraction of collected rainwater, which is effectively reused.

[13] The built density can indirectly influence the transport distances and the efficiency of public transport (an efficient public transport is more difficult to implement in low-built density areas). However, the same transport profile (Flemish average) is assumed for all reference neighbourhood variants in this step of the analysis.

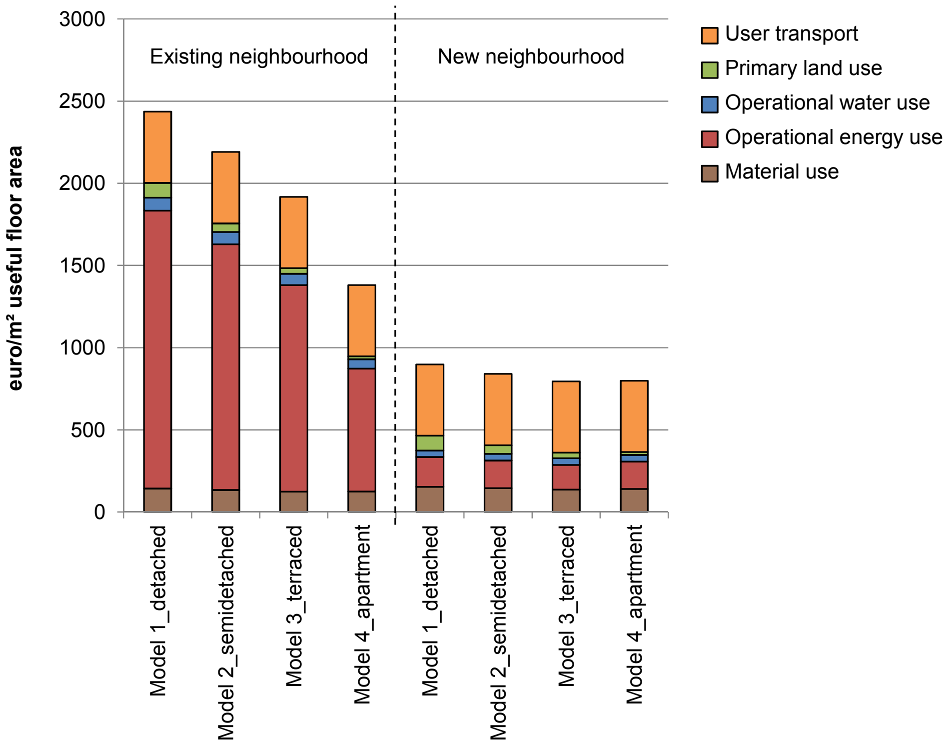

Figure 8.19: Life cycle environmental cost of the reference neighbourhoods, subdivided per driver.

Furthermore, despite the higher built density, the new neighbourhood variant consisting of apartments has a similar life cycle environmental cost to the model with terraced houses. The main reason is the lower PV electricity production in the model consisting of apartments (8 kWh/m² UFA instead of 19 kWh/m² UFA for the single-family houses).

When looking at the contribution of the various drivers (Figure 8.19), operational energy use is the main contributor to the life cycle environmental impact of the existing neighbourhood variants (i.e. about 55-70%). Another major contributor is user transport which represents about 20-30% of the life cycle impact. Material use, operational water use and primary land use have a contribution lower than 10%.

In the new neighbourhoods, user transport is the main contributor (about 50-55% of the life cycle environmental cost), followed by operational energy use (about 20%) and material use (about 17%). As for the existing neighbourhood variant, the contribution of operational water use and primary land use does not exceed 10%.

The contribution of the various drivers can however vary importantly depending on the impact indicator. This is illustrated in Figure 8.20, based on the new neighbourhood variant consisting of detached houses. The figure shows that user transport is the main contributor for 12 of the 18 impact categories. Nevertheless, primary land use is by far the main contributor to the land use impact categories. Furthermore, material use and operational water use are the main contributors to the indicators depletion of abiotic resources (elements) and water scarcity respectively.

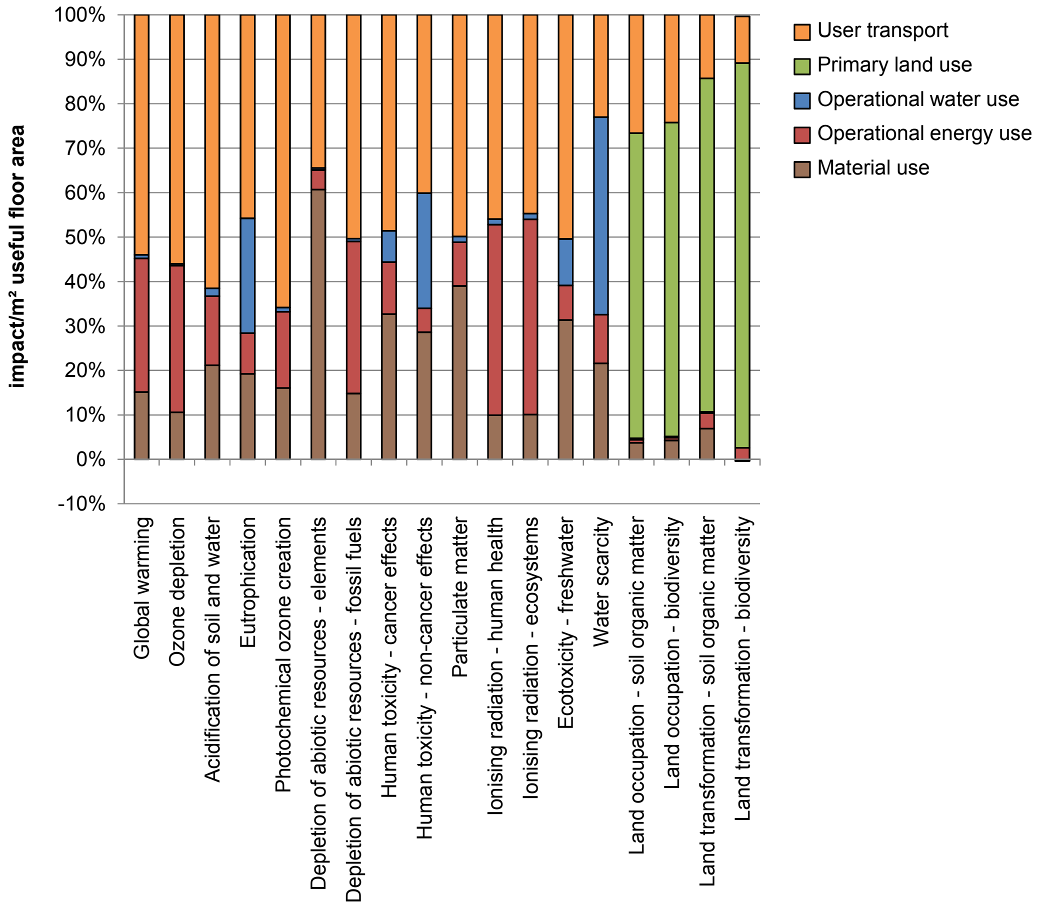

Figure 8.20: Relative contribution of the drivers to the life cycle environmental impacts of the neighbourhood model with detached houses (new neighbourhood variant).

The life cycle environmental cost of the neighbourhood reference variants is shown per life cycle module in Figure 8.21. The use stage contributes to about 90-95% of the life cycle environmental cost. Main contributors to the use stage are operational energy use (module B6) and user transport (module B9), which together contribute to about 70-90% of the life cycle environmental cost.

When analysing the contribution of the impact categories (Figure 8.22), the indicator global warming is by far the main contributor and represents about 70-75% of the life cycle environmental cost of the existing neighbourhood variants. The contribution of other impact categories do not exceed 10%. As already mentioned in Chapter 7, the high contribution of global warming is a result of the high valuation of this impact category in the recent update of the MMG monetisation method (De Nocker and Debacker 2015)[14]. Concerning the new neighbourhood variants, the impact of global warming is reduced by 50 to 70% compared to the existing variants. This is due to the high reduction of the operational energy use, which is a high contributor to this impact category. However, the relative contribution of global warming to the new variants remains high (i.e. about 60% of the life cycle impact).

[14] In the updated method, global warming is valued 0.1 €/kg CO_2 equiv. for the central scenario, instead of 0.06 €/kg CO_2 equiv. in the original method (Allacker et al. 2013b; De Nocker and Debacker 2015).

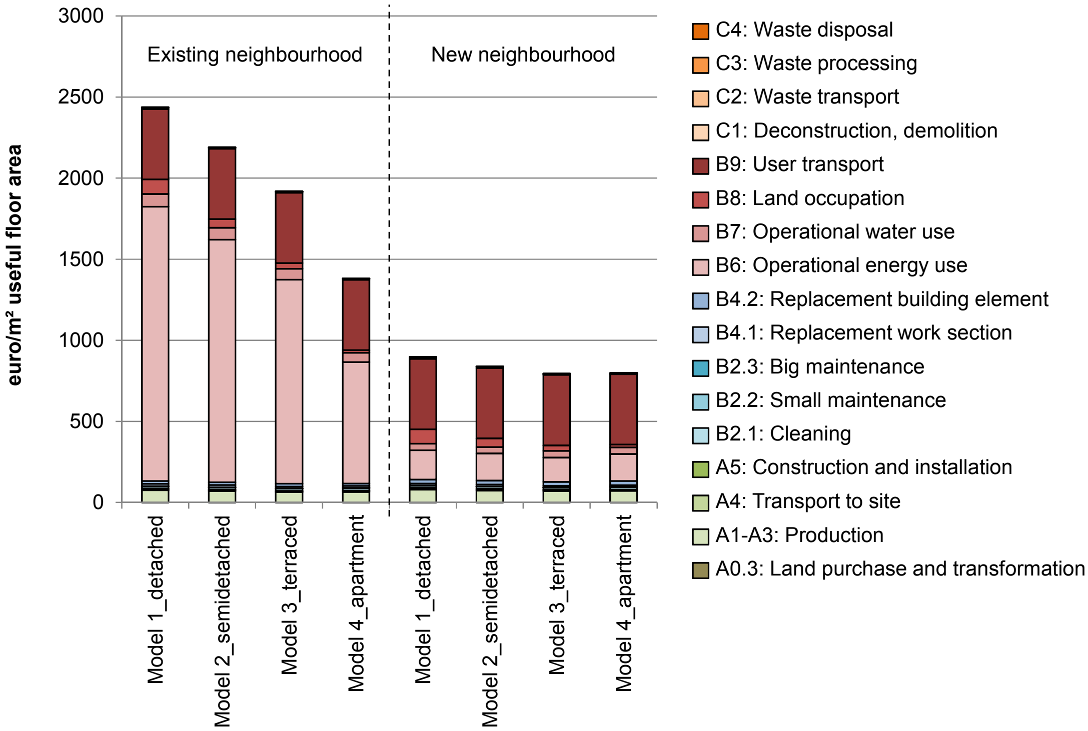

Figure 8.21: Life cycle environmental cost of the reference neighbourhoods, subdivided per life cycle module.

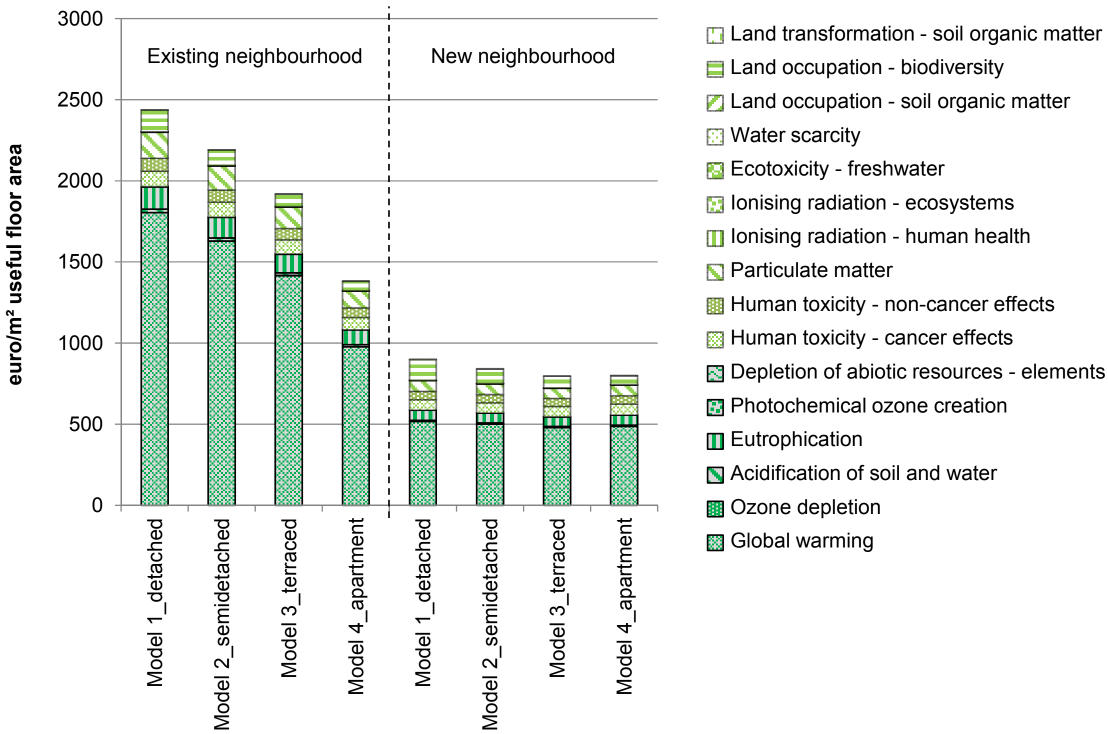

Figure 8.22: Life cycle environmental cost of the reference neighbourhoods, subdivided per impact category.

8.3.3 Financial impact

The life cycle financial cost of the reference neighbourhood variants is shown in Figure 8.23. Cost reductions of up to 20% are obtained for the new neighbourhoods compared to the existing ones. These reductions are lower compared to the environmental cost, due to the lower contribution of energy use to the life cycle financial cost.

Concerning the impact of the urban form and built density, the variations are also larger for the existing neighbourhood variants. In that case, the life cycle financial cost of the model consisting of apartments is 28% lower than the model with detached houses. For the new neighbourhood variants, the reduction between both models is limited to 19%. As for the environmental cost, the new neighbourhood consisting of apartments has a similar life cycle financial cost to the terraced house model, despite the higher built density. The reason is again the lower PV electricity production in the model consisting of apartments.

When analysing the contribution of the various drivers (Figure 8.23), the global picture is quite different from the environmental cost. The material use is the main contributor and represents about 45-55% of the life cycle financial cost of all variants. Another major contributor is user transport (about 20-35%). The contribution of operational energy use varies from about 6-7% in the new variants to about 15-25% in the existing variants. The contribution of operational water use and primary land use do not exceed 10% of the life cycle financial cost. The only exception is the new neighbourhood with detached houses where primary land use contributes to 12% of the life cycle financial impact.

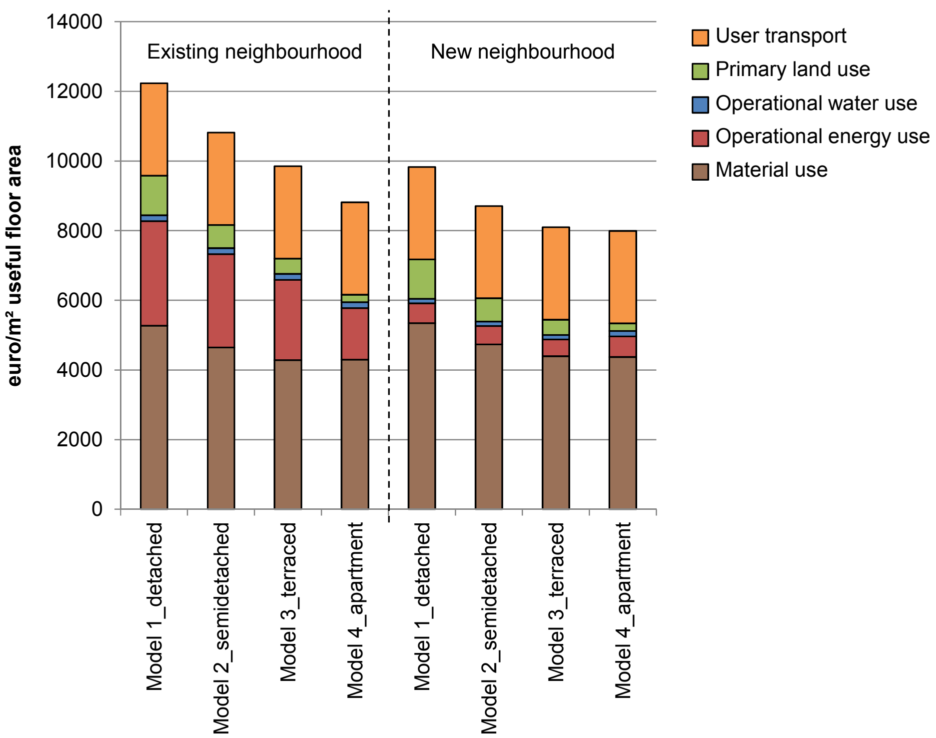

Figure 8.23: Life cycle financial cost of the reference neighbourhoods, subdivided per driver.

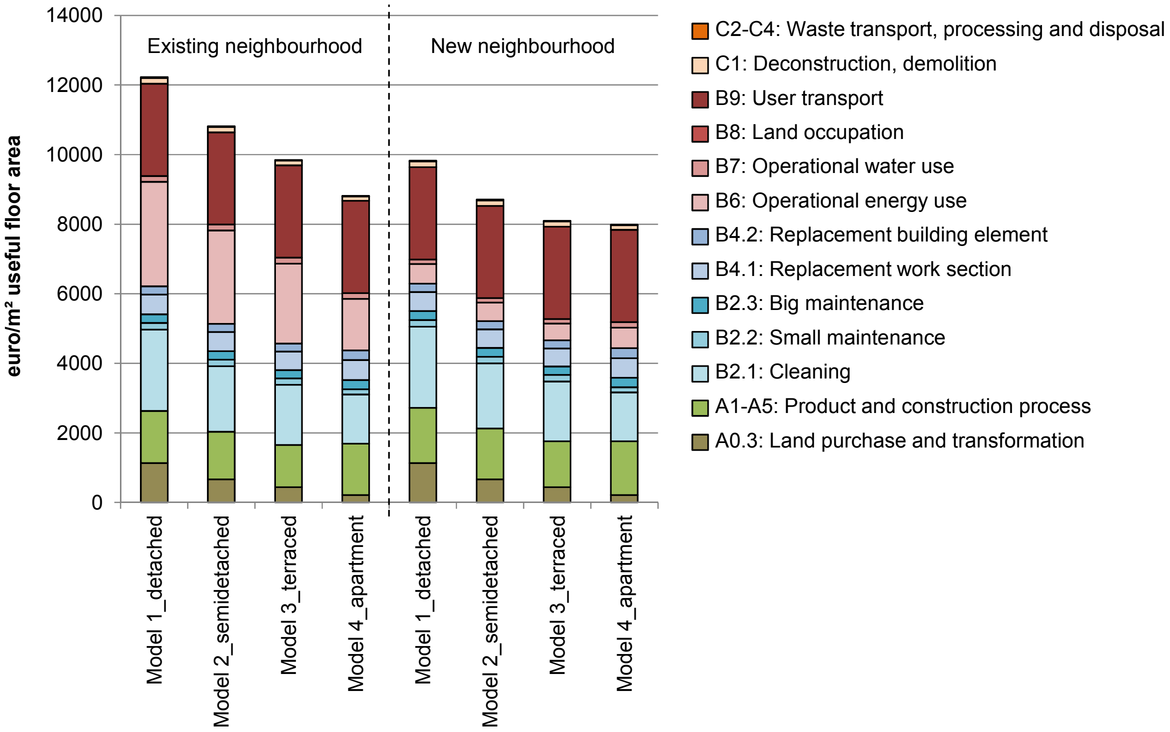

Figure 8.24: Life cycle financial cost of the reference neighbourhoods, subdivided per life cycle module.

The life cycle financial cost of the neighbourhood reference variants is shown per life cycle module in Figure 8.24. The use stage is responsible for about 70-80% of the life cycle financial cost. The main contributors to the use stage are user transport (module B9), operational energy use (module B6) and cleaning (module B2.2). The high cost of cleaning activities is a result of the high frequency of these processes and the assumption that cleaning is exclusively done by professionals. While the impact of operational energy use decreases importantly for the new variants, the impact of other life cycle modules remains almost the same, leading to an increase of their relative contribution. Furthermore, the before use stage (module A), which corresponds to the investment cost, contributes about 15-30% to the life cycle financial cost.

8.3.4 Total cost

Based on the life cycle financial and environmental cost, the life cycle total cost of the neighbourhood reference variants is calculated (Figure 8.25). The results show a similar picture as for the financial cost because the environmental cost represents only 10-15% of the total cost.

As the internalisation of the external environmental cost does not influence decisions based on financial cost, the results for the total cost are not reported separately for the assessment of other neighbourhood variants in the subsequent parts of this chapter.

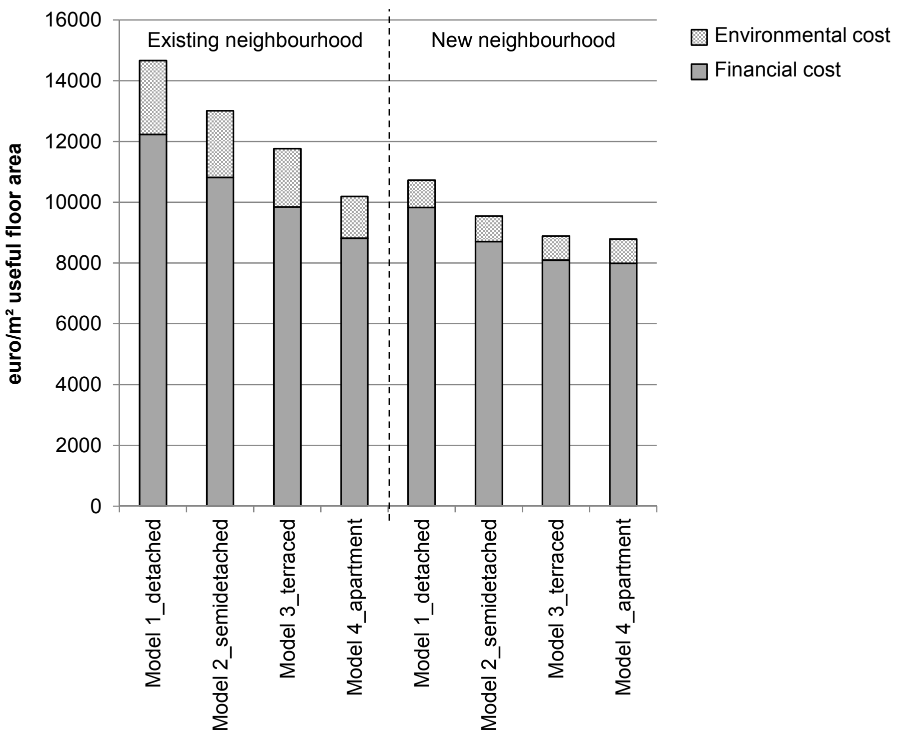

Figure 8.25: Life cycle total cost of the reference neighbourhoods, subdivided in financial and environmental cost.

8.4 Assessment of material use

8.4.1 Contribution of building elements and external elements

Environmental impact

The contribution of the various elements to the environmental impact of material use in the existing and new neighbourhood variants is shown in Figure 8.26. The material impact of the new neighbourhoods is 7 to 13% higher compared to the existing ones. This is mainly due to an impact increase of electrical services (6) resulting from the installed PV system and of higher insulation levels applied in the new variants. This impact increase is however largely offset by the decrease in the impact of operational energy use (Figure 8.19).

When analysing the impact of the built density, reductions in material environmental cost up to 14% are noticed between the models consisting of detached and terraced houses. Despite the higher built density, the model consisting of apartments has a slightly higher impact than the terraced house model. This is due to the additional impact of the collective circulation spaces (resulting in an increase in the floor area of 15%) and the high impact of pile foundations in apartment buildings.

The contribution of the external elements (94, 95 and 96) varies from 8-9% for the apartment model to 17-18% for the detached house model. This variation is mainly due to the difference in impact of the roads (higher amount in the detached house model).

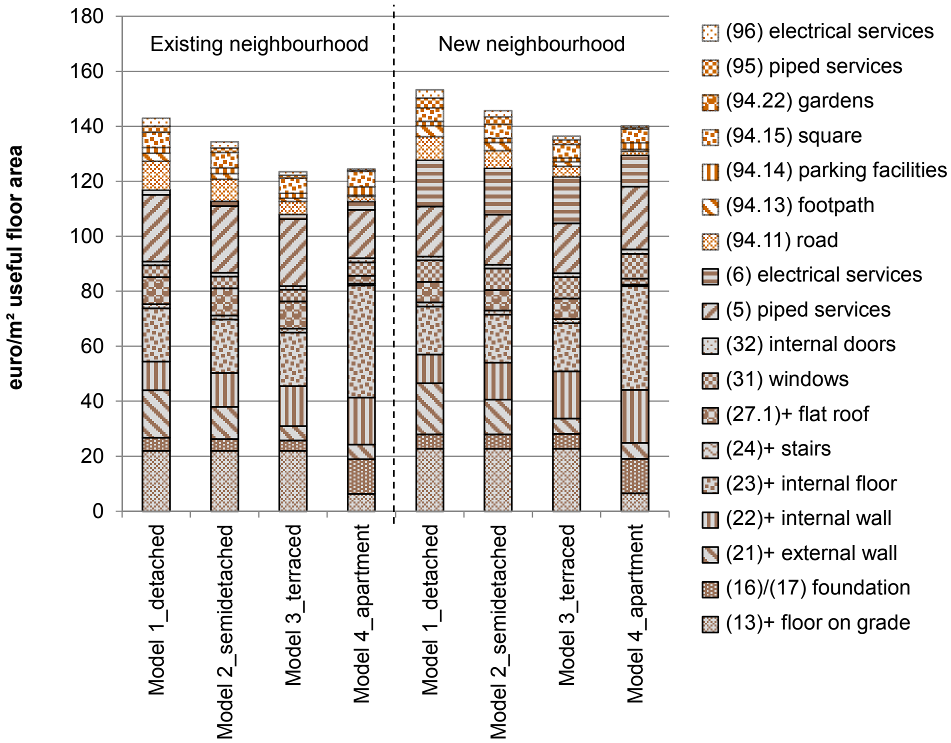

Figure 8.26: Environmental cost of material use for the reference neighbourhoods, subdivided per building and external element.

Regarding the impact of the building elements, the floor on grade, external and internal walls, internal floors and piped services contribute mostly to more than 10% of the material environmental cost for the majority of the reference neighbourhoods consisting of single-family houses. Electrical services (6) only cause a significant impact in the new neighbourhoods, due to the installed PV system. For the apartment model, the main contributor is the internal floors, followed by the internal walls, piped services and pile foundations. As could be seen from the calculated ratios (Figure 8.18), the contribution of the building envelope elements (i.e. floor on grade, external wall and roof) decreases for more compact buildings, such as terraced houses and apartments, but is partially compensated by an increase of the contribution of the internal building elements (i.e. internal wall and floor).

Financial impact

The contribution of the elements to the financial impact of material use in the neighbourhood variants is shown in Figure 8.27. Unlike the environmental cost, the new neighbourhoods result in only a slight increase of about 1-3% of the material financial cost compared to the existing neighbourhoods. The reason is the lower financial cost of the piped services in the new variants, including a condensing gas instant boiler instead of a more expensive oil boiler[15] with storage vessel. Furthermore, the PV system has a lower influence on the material financial cost than on the material environmental cost.

[15] The investment and maintenance cost of an oil boiler are higher than for a gas boiler. Also the oil storage tank has a high financial impact.

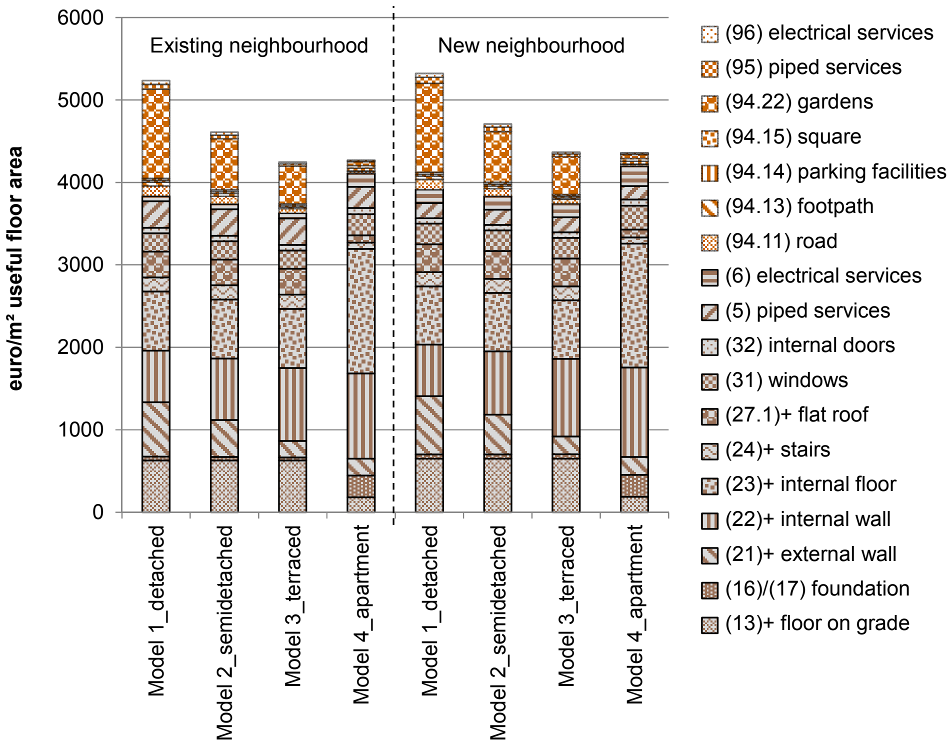

Figure 8.27: Financial cost of material use for the reference neighbourhoods, subdivided per building and external element.

As for the environmental cost, the built density has a relatively high influence on the financial impact of material use. Reductions in material financial cost up to 19% are noticed between the models consisting of detached and terraced houses. Despite the higher built density, the apartment model has a similar impact as the terraced house model. This is again a result of the additional impact of the collective circulation spaces and the high financial cost of pile foundations in apartment buildings.

The contribution of the external elements (94, 95 and 96) to the material financial cost varies from 4% for the model consisting of apartments to 27% for the model consisting of detached houses. Unlike the environmental cost, this variation results mainly from the financial cost of the gardens[16] which increases from 1% of the material financial cost in the apartment model to about 20% in the model consisting of detached houses.

Regarding the impact of the building elements, the floor on grade, external walls, internal walls and internal floors contribute to more than 10% of the material financial cost in the majority of the neighbourhood models consisting of single-family houses. For the neighbourhood consisting of apartments, the main contributors are the internal floors and walls, which contribute together to more than 50% of the material financial cost. As for the environmental cost, the contribution of the building elements is influenced by the built density, with a shift from building envelope to internal elements for more compact buildings.

[16] The high financial cost of the gardens is a result of the high frequency of grass cutting and the high cost for cutting and trimming the hedges (see Chapter 7).

8.4.2 Material related sustainability measures

Description of the analysed measures

Two strategies to reduce the material impact are defined. The first measure (M1_timber[17]) focuses on the use of a timber structure and finishes in buildings. The timber structure consists of a wood skeleton filled with stone wool insulation. The same insulation levels as for the reference solid structure are used (EPB 2017 standard). Besides the structural parts, the building elements (Table 8.9) are characterised by a maximal use of timber products including a parquet floor finish (instead of tiles), an external wall finish in cedar planks (instead of facing brick), wooden window frames (instead of PVC) and wooden stairs (instead of concrete stairs). For the apartment model, the load-bearing elements are solid variants while timber variants are selected for the windows and non-load-bearing internal walls, as apartment buildings are exposed to higher vertical loads and have to fulfil stricter fire safety regulations.

In the second sustainability measure (M2_recycled materials) the use of recycled materials for the paved areas (i.e. roads, footpaths, parking facilities and square) is investigated, including a surface layer in reclaimed cobblestones and a base and sub-base of crushed rubble (instead of gravel). The analysed external elements are summarised in Table 8.8.

Table 8.8: External elements of the variant composed of recycled materials for the paved areas (M2_recycled materials). The adaptations to the reference new variant are indicated in green/italics.

External element	Composition
(94.11) road	Geotextile – *crushed rubble sub-base* – *cement bound crushed rubble base* – *cobblestones*
(94.13) footpath	Geotextile – *cement bound crushed rubble base* – *cobblestones*
(94.14) parking facilities	Geotextile – *crushed rubble sub-base* – *cement bound crushed rubble base* – *cobblestones*
(94.15) square	Geotextile – *crushed rubble sub-base* – *cement bound crushed rubble base* – *cobblestones*
(94.22) gardens	Grass and hedges
(95) piped services	Concrete storm sewer and vitrified clay sanitary sewer – drainage ditches – drinking water and gas pipes (HDPE)
(96) electrical services	Electric and data cables

[17] The sustainability measures are numbered based on the following convention:

- The letter code refers to the analysed driver ("M" for material use, "E" for operational energy use, "W" for operational water use, "L" for primary land use and "T" for user transport)
- The digit code is used to make a distinction between the sustainability measures of one driver. For example, "M2" refers to the second sustainability measure related to material use.

Table 8.9: Building elements of the timber variant (M1_timber). The adaptations to the reference new variant are indicated in green/italics.

Building element	Composition	U-value (W/m²K)
(13)+ floor on grade	Concrete slab 15 cm – PUR board 9 cm – screed mix – *parquet*	0.23
(16)+ foundation	In situ concrete foundation	n/a
(17)+ pile foundation	Prefab concrete piles	n/a
(21)+ external wall	*Cedar planks* – *timber frame + stone wool 20 cm* – *plasterboard* – acrylic paint	0.23
(22.1)+ load-bearing internal wall	Acrylic paint – *plasterboard* – *timber frame + stone wool 14 cm* – *plasterboard* – acrylic paint	n/a
(22.3)+ non-load-bearing internal wall	Acrylic paint – *plasterboard* – *timber frame + stone wool 10 cm* – *plasterboard* – acrylic paint	n/a
(22.8)+ party wall	Acrylic paint – *plasterboard – timber frame + stone wool 14 cm* – *rock wool 6 cm* – *timber frame + stone wool 14 cm* – *plasterboard* – acrylic paint	n/a
(23)+ storey floor	Acrylic paint – *plasterboard* – *wooden beams 22 cm* – *stone wool 3cm* – *OSB* – *parquet*	n/a
(23)+ party floor	Acrylic paint – *plasterboard* – *wooden beams + stone wool 22 cm* – *stone wool 3cm* – *OSB* – *parquet*	n/a
(24)+ stairs	*Wooden closed staircase* – *varnish* – *wooden banister*	n/a
(27.1)+ flat roof	EPDM – *stone wool 14 cm* – *OSB* – *slope wedges* – *wooden beams 22 cm* – *plasterboard* – acrylic paint	0.24
(31) windows	*Painted wood frame* – thermally improved double glazing (g-value = 0.61)	1.44
(32) internal doors	MDF frame – plain door	n/a
(5) piped services	Condensing gas boiler – panel radiators – coupled instant hot water production – ventilation type C – rainwater tank	n/a
(6) electrical services	Electric cables – (elevators) – PV panels	n/a

Environmental impact

The environmental cost of the sustainability measures related to material use is shown in Figure 8.28. Reductions of the environmental impact of material use of 18-19% are obtained by the timber variants compared to the reference variants, for the models consisting of single-family houses. For the apartment model, the reduction is limited to 3% as only the composition of the non-load-bearing internal walls and windows is modified.

Compared to the reference variants, the reduction of the material environmental cost due to the use of recycled materials for paved areas varies from 3% for the apartment model to 5% for the detached house model. The reductions are limited due to the small contribution of external elements to the impact of material use.

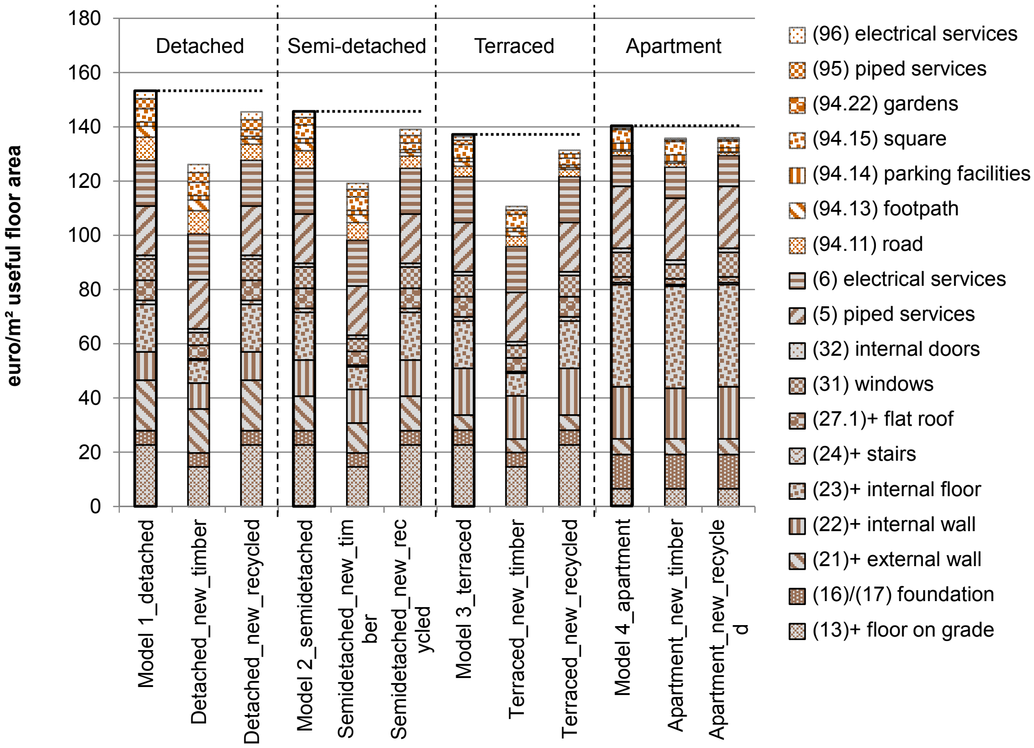

Figure 8.28: Environmental cost of the sustainability measures related to material use, applied to the reference new neighbourhoods. Only the impact of material use is shown as other drivers are not influenced by the sustainability measures.

Financial impact

A different picture is obtained for the financial results (Figure 8.29) as the measures mostly lead to an increase of the cost of material use compared to the reference variants. The timber frame variants are characterised by an increase in material financial cost that ranges from 5% for the terraced house model to 18% for the detached house model. This increase is mainly due to the higher financial cost of the external walls resulting from the cleaning of cedar planks. As the ratio of external walls is higher in the models consisting of detached and semi-detached houses, the cost increase is higher for these models. For the apartment model, a small reduction of 2% of the material financial cost is obtained due the slightly lower financial cost of the wooden windows and non-load-bearing internal walls in timber frame compared to the solid variants.

The use of recycled materials for paved areas, leads to an increase in material financial cost ranging from 2% for the apartment model to 3% for the detached house model. This is due to the high financial cost of the cobblestones (see Chapter 7). As the paved areas contribute to a limited extend to the material financial cost, the increase is relatively limited.

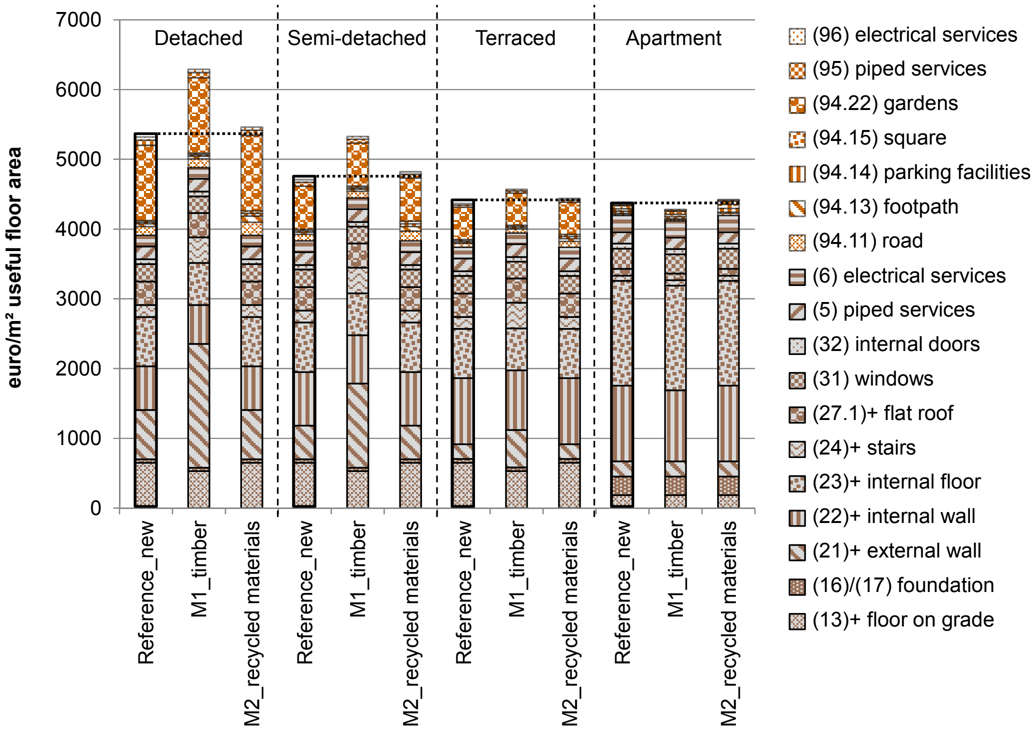

Figure 8.29: Financial cost of the sustainability measures related to material use, applied to the schematic neighbourhood models. Only the impact of material use is shown as other drivers are not influenced by the sustainability measures.

8.5 Assessment of operational energy use

8.5.1 Heating energy demand calculations

The heating energy demand of the housing units in the four schematic neighbourhood models is calculated based on the dEHDD method using the EPB+ approach (see Chapter 5). Three energy performance levels are considered (Table 8.10), whereof the impact is analysed separately in section 8.5.3. The first level corresponds to the reference variant for new neighbourhoods in line with the current EPB regulation (2017). The second level is representative for existing 'old' neighbourhoods, i.e. a non-insulated situation with a high air infiltration rate of 12 m³/h.m². The third level corresponds to the passive standard with a high insulation level, a low air infiltration rate (1 m³/h.m²) and a mechanical ventilation with heat recovery (System D+). For the heat recovery an efficiency of 85% is assumed.

Table 8.10: Energy performance levels analysed

Parameter	REF_EPB 2017 standard	E1_non-insulated	E2_passive standard
Insulation level	Max U-values EPB 2017	No insulation	Max U-values PHPP
Air infiltration rate	6 m³/h.m²	12 m³/h.m²	1 m³/h.m²
Ventilation system	Natural supply and mechanical exhaust (system C)	Natural ventilation (system A)	Mechanical supply and exhaust + heat recovery (system D+)

The results of the heating energy demand calculations are shown in Figure 8.30. For the EPB 2017 variant, the detailed results per housing unit in the four neighbourhood models are visualised in Figure 8.31. Significant variations are noticed between the four neighbourhood models with differences in average heating energy demand up to 182 kWh/m².year, 28 kWh/m².year and 9 kWh/m².year for respectively the non-insulated, EPB 2017 and passive variant. This is a consequence of the variations in building compactness resulting from the neighbourhood layouts. Detached houses have higher heat transmission losses through the building envelope per m² floor area, compared to clustered housing units in apartment buildings. The reduction in heating energy demand however tends to flatten for a high increase in built density, especially in low energy (EPB 2017) and passive neighbourhoods (Figure 8.30). The reason is the reduced availability of solar radiation in the model consisting of apartments. This is especially true in the housing units located on the lower floors and with a street façade oriented to the south (Figure 8.31).

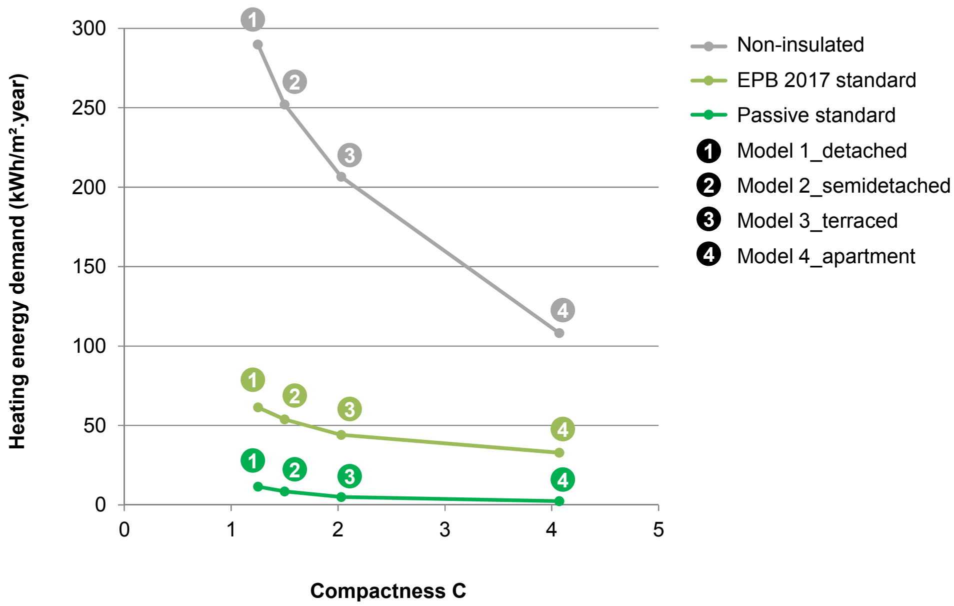

Figure 8.30: Average heating energy demand of the neighbourhood models, calculated for three energy performance standards (Not insulated, EPB 2017 and passive standard)

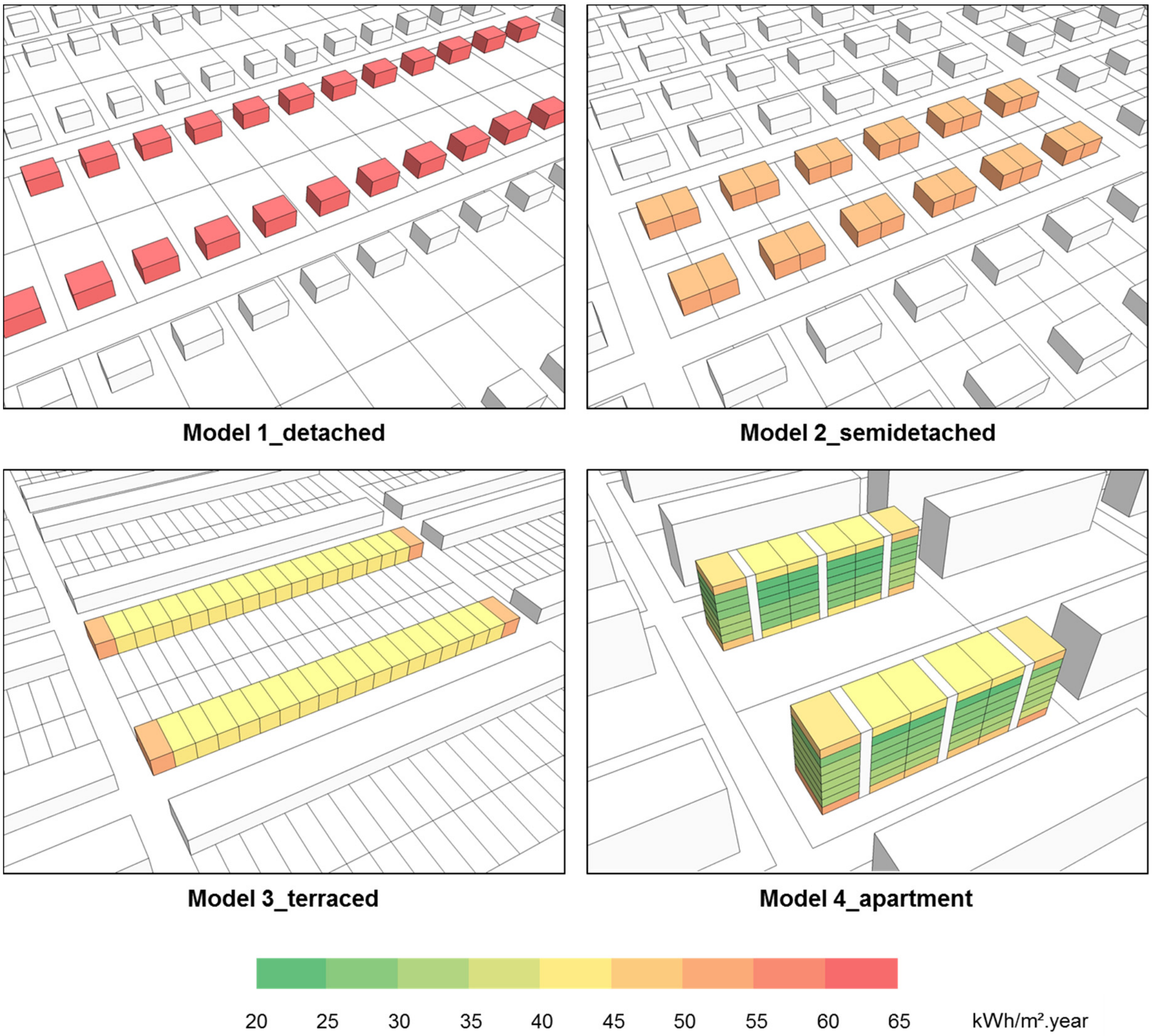

Figure 8.31: Heating energy demand per m² UFA for the different housing units in the reference new neighbourhoods (EPB 2017 standard), visualised by colour.

8.5.2 Contributors to the impact of operational energy use

Environmental impact

The environmental cost of operational energy use, subdivided per contributor, is shown in Figure 8.32 for the existing and new neighbourhoods. As already mentioned, the impact of energy use is much lower (up to 90%) for the new variants compared to the existing ones. The main reason is the reduction of the impact of energy use for heating by about 90%.

In case of the existing neighbourhood variants, the urban form and density clearly have an influence on the environmental cost of operational energy use. The environmental cost of the operational energy use of the apartment model is about 55% lower than of the detached house model. The variations are much lower for the new neighbourhood variants, with reductions up to about 15% for the terraced house model. This is a consequence of the lower contribution of the impact of space heating in the new variants. Despite the higher built density, the energy environmental cost of the apartment model is higher than for the terraced house model due to the lower electricity production by the PV system.

The analysis of the various energy contributors for the existing neighbourhood variants shows that space heating is by far the main contributor (about 75-90%). The contribution of domestic hot water, lighting and appliances and road lighting do not exceed 10% for the models consisting of single-family houses. For the apartment model, energy use for domestic hot water and lighting and appliances contribute to about 12-13% of the energy environmental cost.

Concerning the new neighbourhood variants, space heating is still the main contributor for the single-family houses (about 50-55%), followed by lighting and appliances (about 20-25%) and the production of domestic hot water (about 15-20%). The contributions of energy use for ventilation and road lighting do not exceed 10%. The order differs for the apartment model where energy use for appliances and lighting is the main contributor (44% of the energy environmental cost), followed by energy use for heating (32%) and domestic hot water (17%). This is again a consequence of the lower electricity production from the PV-system in apartment buildings.

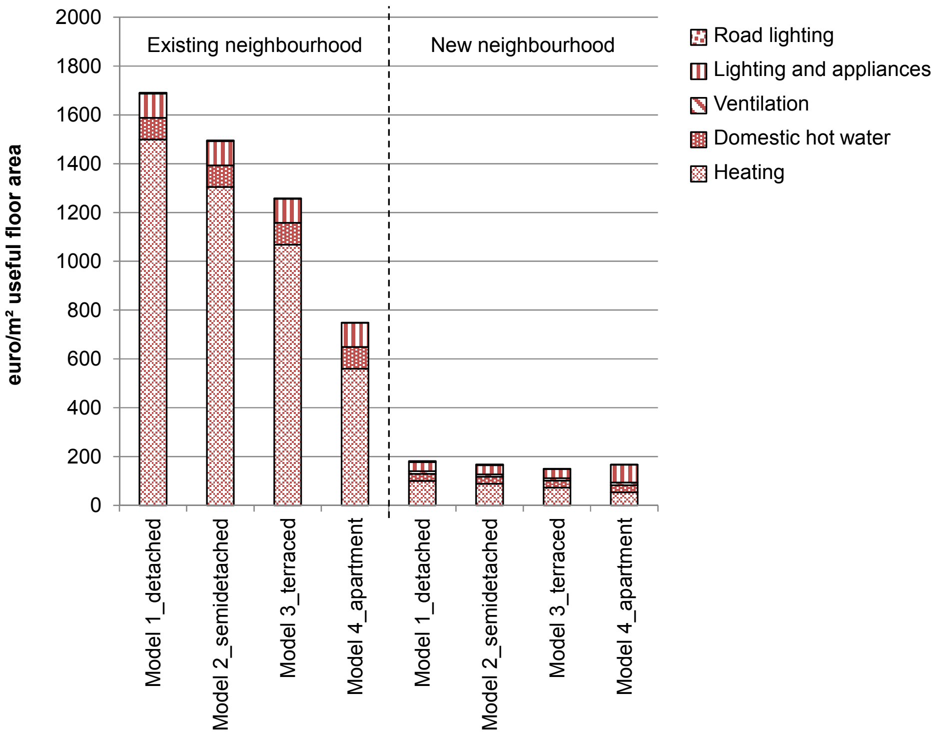

Figure 8.32: Environmental cost of operational energy use for the reference neighbourhoods, subdivided per energy contributor.

Financial impact

A similar picture is obtained for the financial cost of operational energy use (Figure 8.33). The financial cost of operational energy of the new neighbourhood variants is about 60 to 80% lower than of the existing variants.

Similar as for the environmental cost, the influence of the urban form and density is bigger for the existing neighbourhoods with energy cost reductions up to about 50% for the apartment model. For the new variants the reductions are limited to about 15% for the terraced house model. Despite the higher built density, the apartment model has the highest energy cost of all new neighbourhood variants due to the lower electricity production by the PV-system.

Regarding the analysis of the energy contributors for the existing neighbourhoods, space heating is the main contributor (60 to 80% of the energy financial cost). The contribution of lighting and appliance (15 to 30%) is much higher than for the environmental cost due to the high financial cost of electricity compared to other energy sources (see Chapter 5). Domestic hot water production and road lighting do not contribute more than 10% in any of the models.

Concerning the new neighbourhoods, space heating is the main contributor for the models consisting of single-family houses (about 40%-45% of the energy cost), followed by lighting and appliances (about 30-35%) and domestic hot water production (about 15%). Similar as for the environmental cost, the order differs for the apartment model where lighting and appliance contribute most (55% of the energy cost), followed by space heating (24%) and domestic hot water production (13%).

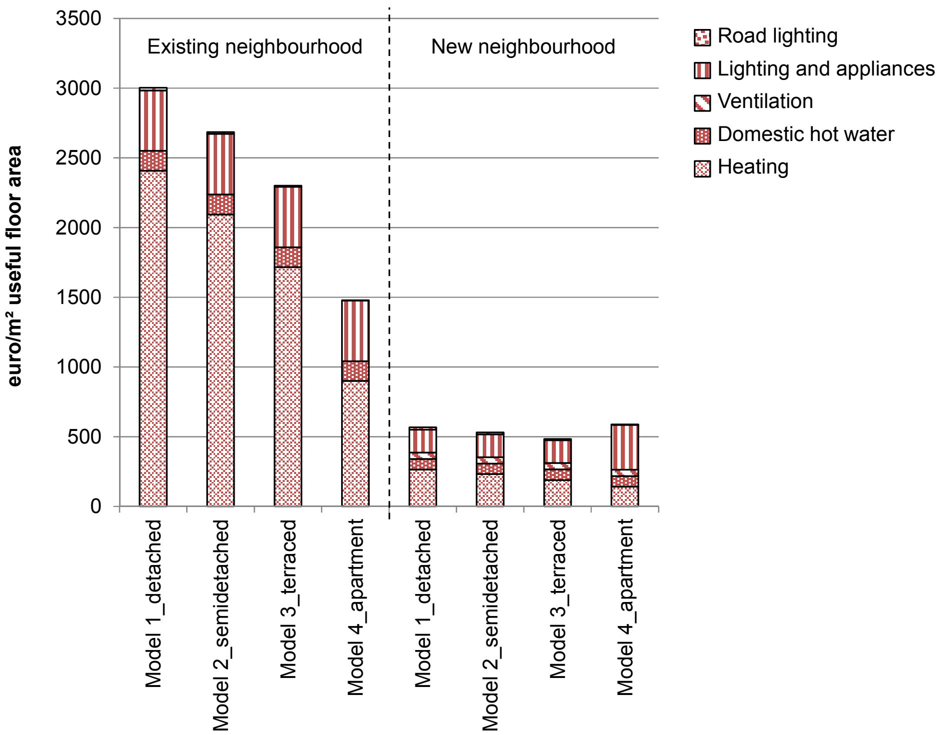

Figure 8.33: Financial cost of operational energy use for the reference neighbourhoods, subdivided per energy contributor.

8.5.3 Energy related sustainability measures

Description of the analysed measures

Three types of strategies related to operational energy use are investigated. The first type of measures are related to the energy performance level, including the insulation level, air tightness and ventilation system (Table 8.10). Compared to the reference variant (EPB 2017 standard), a non-insulated situation (E1_non-insulated) and the passive standard (E2_passive standard) are considered. The building elements considered for the non-insulated situation are similar to the ones used in the existing neighbourhood variants (Table 8.4). For the piped and electrical services, the new element variants are selected (Table 8.6)[18], as the influence of the technical system is analysed in a second step. The building elements of the passive variant are summarised in Table 8.11.

Table 8.11: Building elements of the passive variant (E2_passive standard). The adaptations to the reference new variant are indicated in green/italics.

Building element	Composition	U-value (W/m²K)
(13)+ floor on grade	Concrete slab 15 cm – *PUR board 15 cm* – screed mix – fired clay tiles	*0.15*
(16)+ foundation	In situ concrete foundation	n/a
(17)+ pile foundation	Prefab concrete piles	n/a
(21)+ external wall	Facing brick – *PUR board 14 cm* – insulating hollow brick 14 cm – gypsum plaster – acrylic paint	*0.14*
(22.1)+ load-bearing internal wall	Acrylic paint – gypsum plaster – hollow brick 14 cm – gypsum plaster – acrylic paint	n/a
(22.3)+ non-load-bearing internal wall	Acrylic paint – gypsum plaster – hollow brick 9 cm – gypsum plaster – acrylic paint	n/a
(22.8)+ party wall	Acrylic paint – gypsum plaster – hollow brick 14 cm – stone wool 6 cm – hollow brick 14 cm – gypsum plaster – acrylic paint	n/a
(23)+ storey floor	Acrylic paint – gypsum plaster – hollow core concrete slab 12 cm – pressure layer – screed mix – fired clay tiles	n/a
(23)+ party floor	Acrylic paint – gypsum plaster – hollow core concrete slab 12 cm – pressure layer – rock wool 3 cm – screed mix – fired clay tiles	n/a
(24)+ stairs	Concrete staircase – metal banister	n/a
(27.1)+ flat roof	EPDM – *PIR board 17 cm* – concrete slope layer – hollow core concrete slab 12 cm – pressure layer – gypsum plaster – acrylic paint	*0.15*
(31) windows	*Thermally improved PVC frame* – *triple glazing (g-value = 0.48)*	*0.69*
(32) internal doors	MDF frame – plain door	n/a
(5) piped services	Condensing gas boiler – panel radiators – coupled instant hot water production – *ventilation type D+* – rainwater tank	n/a
(6) electrical services	Electric cables – (elevators) – PV panels	n/a

[18] For the piped services, only the ventilation system differs as system A is applied in the non-insulated situation instead of system C in the reference new variant.

The second type of measures relate to the technical system for heating and domestic hot water (Table 8.12). Compared to the condensing gas boiler of the reference variant, an 'old' technical system consisting of a non-condensing oil boiler (E3_oil boiler)[19] and an energy-efficient system consisting of an air/water heat pump (E4_heat pump) are analysed.

The third type of measures focuses on the impact of the PV system by defining a variant without PV panels (E5_no PV), which is compared to the reference new variant. As already mentioned in section 8.3.1, the reference new variants include a PV-system with a yearly electricity production of 19 kWh/m² UFA for the models consisting of single-family houses and 8 kWh/m² UFA for the apartment model.

Table 8.12: Technical systems analysed for heating and domestic hot water.

Parameter	**REF_gas boiler**	**E3_oil boiler**	**E4_heat pump**
Heating system	- Condensing gas boiler - Radiators – room thermostat – thermostatic valves – outside temperature sensor - $\eta_{H,global}$ = 92%	- Non-condensing oil boiler - Radiators – manual valves - $\eta_{H,global}$ = 42%	- Heat pump air/water - Radiators – room thermostat – thermostatic valves – outside temperature sensor - $\eta_{H,global}$ = 263%
Hot water production	- Coupled instant boiler - $\eta_{HW,prod}$ = 85%	- Storage vessel 120l, coupled to space heating - $\eta_{HW,prod}$ = 55%	- Storage vessel 300l[20], coupled to space heating - $\eta_{HW,prod}$ = 140%

Environmental impact

The environmental cost of the strategies related to operational energy use is shown in Figure 8.34. The total environmental cost for material use and operational energy use is considered as the analysed measures have an impact on both. Compared to the reference variants, some measures result in an increase of the total environmental cost. For the models consisting of single-family houses, the highest increase is obtained for the non-insulated situation (about 90-110%), followed by the variants with an oil boiler (about 75-85%) and without a PV-system (about 15%). The order differs for the apartment model: the variant with an oil boiler has the highest environmental cost (+55%), followed by the non-insulated variant (+39%) and the variant without PV-system (+6%). The reason for this difference is that the energy performance levels have a much higher influence on buildings with a lower compactness (see Figure 8.30). The other sustainability measures lead to a reduction of the total environmental cost with the highest reductions obtained for the passive standard (about 10-20%), followed by the heat pump variants (6-8%).

[19] Although individual oil boilers are not common in apartment buildings, the same technical system is assumed in all neighbourhood models.

[20] A 300 litres storage vessel is installed to reduce the on/off switching of the heat pump in favour of a better efficiency (Allacker 2010).

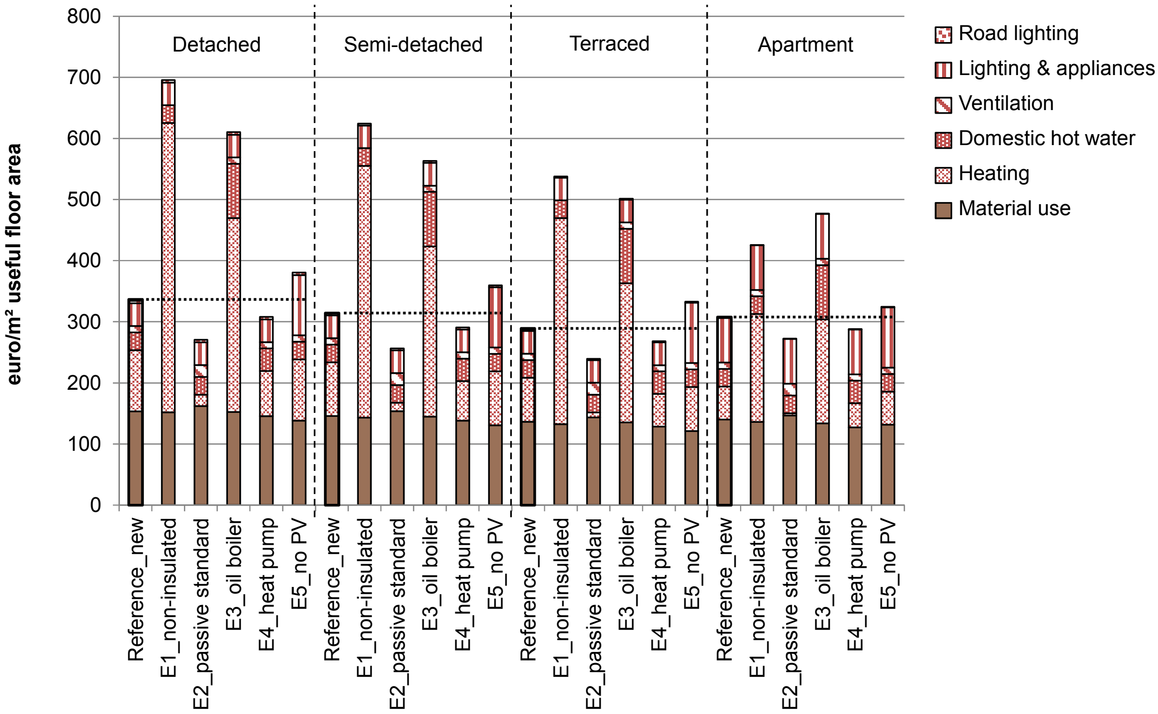

Figure 8.34: Environmental cost of the sustainability measures related to operational energy use, applied to the reference new neighbourhoods.

The high environmental cost for the non-insulated variants compared to the reference variants results from the heating energy cost, which is about 3.25 to 4.75 times higher. Besides the higher heating cost, a slight reduction is noticed for the material environmental cost due to the smaller insulation thicknesses and use of single glazing instead of double glazing.

The heating energy cost of the passive variants decreases by 80-90% compared to the reference variants. This decrease is partially compensated by an increase in material environmental cost of about 5% due to the larger insulation thicknesses, use of triple glazing and mechanical ventilation with heat recovery.

The high impact of the oil boiler variants is due to the increase in environmental energy cost for heating and domestic hot water by a factor 3. This increase is a consequence of both the lower efficiency of the older technical system and the change in fuel used, as the environmental cost of oil is about 40% higher than of natural gas. Concerning the material environmental cost, the oil boiler variants have an impact similar to the reference variants.

Regarding the heat pump variants, the environmental cost reductions are limited because the efficiency gains between a condensing gas boiler (considered in the reference case) and an electric heat pump are (partially) nullified by the high environmental cost of Belgian electricity, which is about twice the cost of natural gas for the same amount of MJ. As a result, the heating energy cost only decreases by about 25% compared to the reference variants while the environmental cost for domestic hot water even increases by about 25% (the efficiency gains from a heat pump are lower for domestic hot water than for space heating). Regarding the material environmental cost, the impact of the heat pump variants is about 5-9% lower compared to the reference variants. This is a consequence of the lower impact for the production of the heat pump and the absence of gas exhaust pipes.

The higher impact of the variants without a PV-system is a consequence of the energy cost for appliances and lighting, which is 165% higher for single-family houses and 35% higher for apartments. The provision of a PV-system has a lower influence on the model consisting of apartments due to the lower roof ratio and resulting PV electricity production (8 kWh/m² UFA instead of 19 kWh/m² UFA for the single-family houses). The variants without a PV-system moreover lead to a reduction of the material environmental cost of about 5% for the apartment model and 10% for the models consisting of single-family houses.

Financial impact

Compared to the environmental impact, the variations in the financial cost of the sustainability measures are smaller (Figure 8.35) due to the lower contribution of operational energy costs. The non-insulated variants, variants with an oil boiler, heat pump and without a PV-system lead to an increase of the total financial cost of material and energy use of about 5-15%, 5-7%, 4-5% and 1-4% respectively compared to the reference variants. Furthermore, the financial impact of the passive variants is similar to the reference variants.

As for the environmental cost, the higher financial cost for the non-insulated variants is a result of the high increase in heating energy cost. Again, this increase is combined with a slight decrease of the material financial cost due to the lower insulation levels.

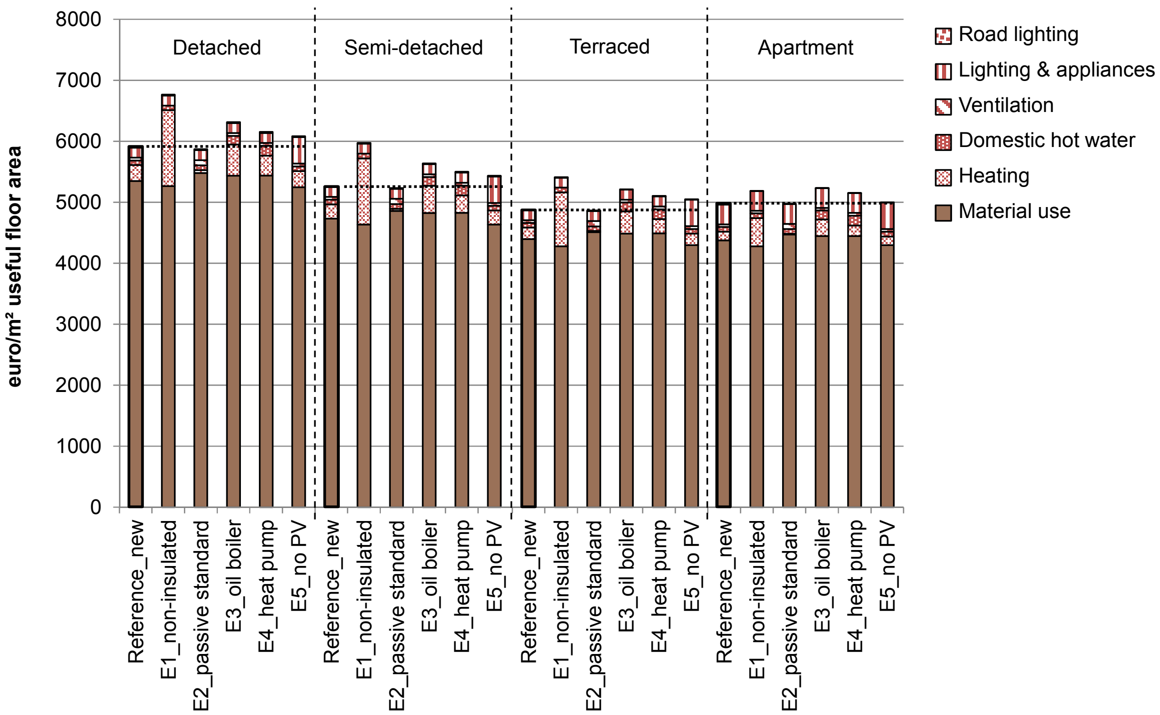

Figure 8.35: Financial cost of the sustainability measures related to operational energy use, applied to the reference new neighbourhoods.

The financial impact of the passive variants is similar to the reference variants because the decrease in heating energy cost is completely compensated by the increase in material cost resulting from the higher insulation levels and improved ventilation system.

For the oil boiler variants, the higher financial cost compared to the reference variants is a result of the increase in energy cost for heating and domestic hot water by about 90%. This increase is much smaller than for the environmental cost as the switch of fuel has a positive financial impact (the financial cost of oil is 13% lower than of natural gas). The material cost of the oil boiler variants is slightly higher compared to the reference variants.

An increase in financial cost is noticed for the heat pump variants which contradicts the environmental cost results. The reason is the high cost of Belgian electricity, which is 3.5 times higher than natural gas. Therefore the efficiency gains for switching from a condensing gas boiler to an electric heat pump are totally nullified by the change of fuel. The energy cost for heating and domestic hot water therefore increases by about 25% and 115% respectively. Regarding the material cost, the impact of the heat pump variants is about 2% higher compared to the reference variants.

As for the environmental impact, the increase of the financial impact for variants without a PV-system is a result of the increase of the energy cost for lighting and appliances. Unlike the environmental cost, only a slight decrease in material cost of about 2% is noticed.

8.6 Assessment of operational water use

8.6.1 Tap water consumption, wastewater and rainwater discharge

The tap water consumption, wastewater and rainwater discharge are calculated for the four schematic neighbourhood models (Figure 8.36), based on the BBRI method (see Chapter 5). When no rainwater tank is installed, the tap water consumption and wastewater discharge are identical for all models because the same total water consumption (435 litres per day per household) is assumed for all cases.

The influence of the urban form and built density can be noticed for the volumes of rainwater discharged. The rainwater discharge from roofs in the apartment model is about 70% lower than for the models consisting of single-family houses. Furthermore, the rainwater discharge from paved areas is up to 50% lower for the apartment model, compared to the detached house model.

The provision of rainwater tanks has an influence on both the tap water consumption and the rainwater discharge from roofs. The tap water consumption is reduced by 24% for the models consisting of single-family houses and 7% for the model consisting of apartments. The lower reduction for the apartment model results from the lower roof ratio in apartment buildings. Concerning the rainwater discharge from roofs, a reduction of about 80% is obtained for all neighbourhood models.

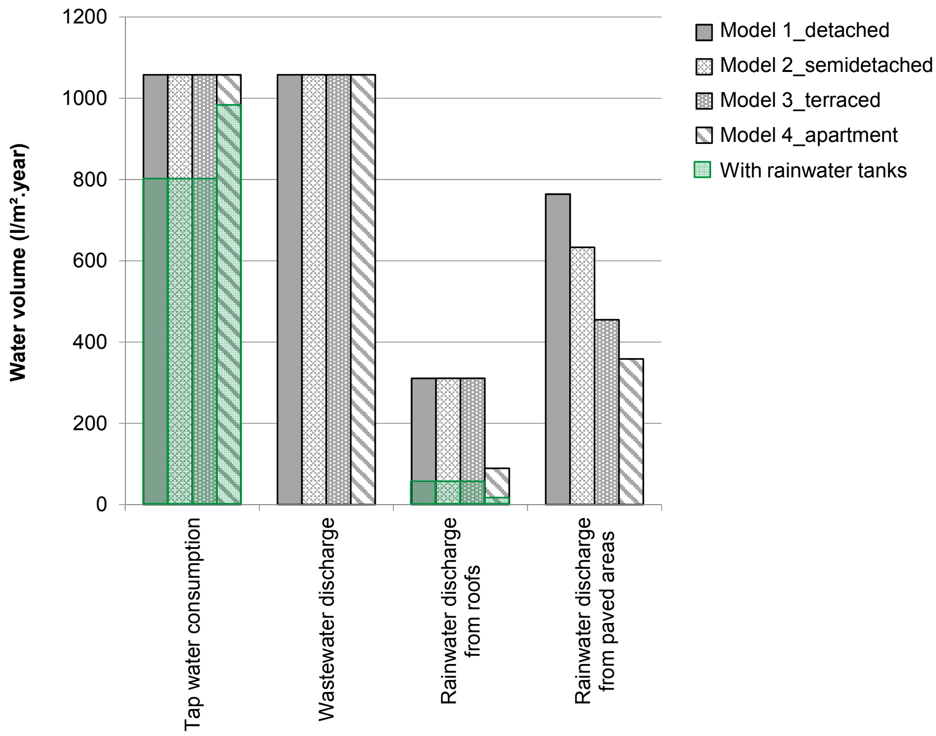

Figure 8.36: Tap water consumption, wastewater and rainwater discharge calculated for the reference neighbourhoods. The results for the scenario with rainwater tanks are indicated in green.

8.6.2 Contributors to the impact of operational water use

Environmental impact

The environmental cost of operational water use, subdivided per contributor, is shown in Figure 8.37 for the existing and new neighbourhoods. Large variations are noticed between the existing and new variants, with impact reductions from about 30% for the apartment model to about 50% for the detached house model. The main reason is the provision of a separate sewer in the new neighbourhood variants to avoid the discharge of rainwater into the sanitary sewer and the related impact for water treatment.

The influence of the urban form and built density is clearly noticeable for the existing neighbourhood variants. Reductions up to 28% are obtained for the apartment model compared to the detached house model. This is a consequence of the lower amount of rainwater discharge to the sanitary sewer in models with a higher built density. Regarding the new neighbourhoods, the water environmental cost is identical for the models consisting of single-family houses due to the provision of a separate sewer. A slightly higher impact is found for the apartment model due to the lower potential for rainwater reuse from roofs.

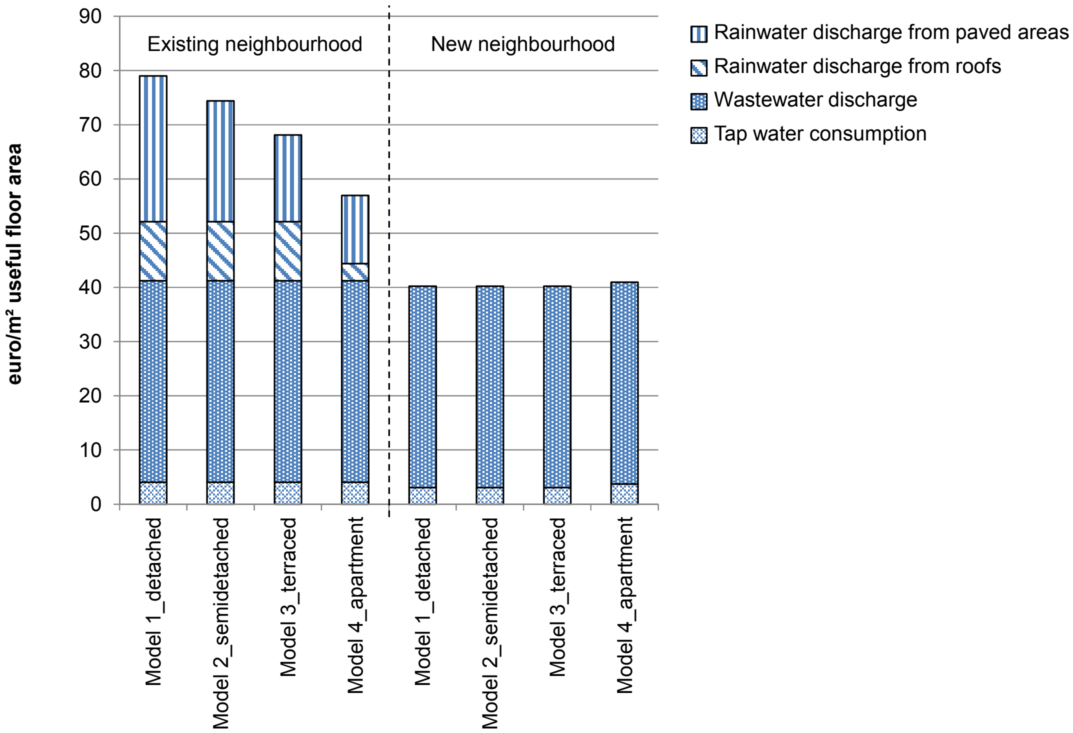

Figure 8.37: Environmental cost of operational water use for the reference neighbourhoods, subdivided per contributor.

When analysing the contributors to the environmental cost of operational water use in the existing neighbourhoods, wastewater discharge is the main contributor (about 50-65%), followed by rainwater discharge from paved areas (about 20-35%) and roofs (about 5-15%). The contribution of the tap water consumption does not exceed 10%. This is a result of the much lower impact of tap water compared to wastewater treatment (see Chapter 5). For the new variants, wastewater discharge is by far the main contributor with a contribution of more than 90% to the water environmental cost.

Financial impact

A different picture is obtained for the financial cost of water use (Figure 8.38) because the financial impact only depends on the tap water consumption and not on the volume of water discharged to the sanitary sewer. Compared to the existing neighbourhood variants, the water financial cost of the new variants is 7% lower for the apartment model and 24% lower for the models consisting of single-family houses. This is a consequence of the reduction of the tap water consumption when rainwater tanks are installed.

Regarding the impact of the urban form and built density, the same water financial cost is obtained for all existing neighbourhoods, as the tap water consumption is identical in all models. For the new neighbourhoods, the water impact is 23% higher for the apartment model compared to the models consisting of single-family houses. The reason is again the lower potential for rainwater reuse from roofs in apartment buildings.

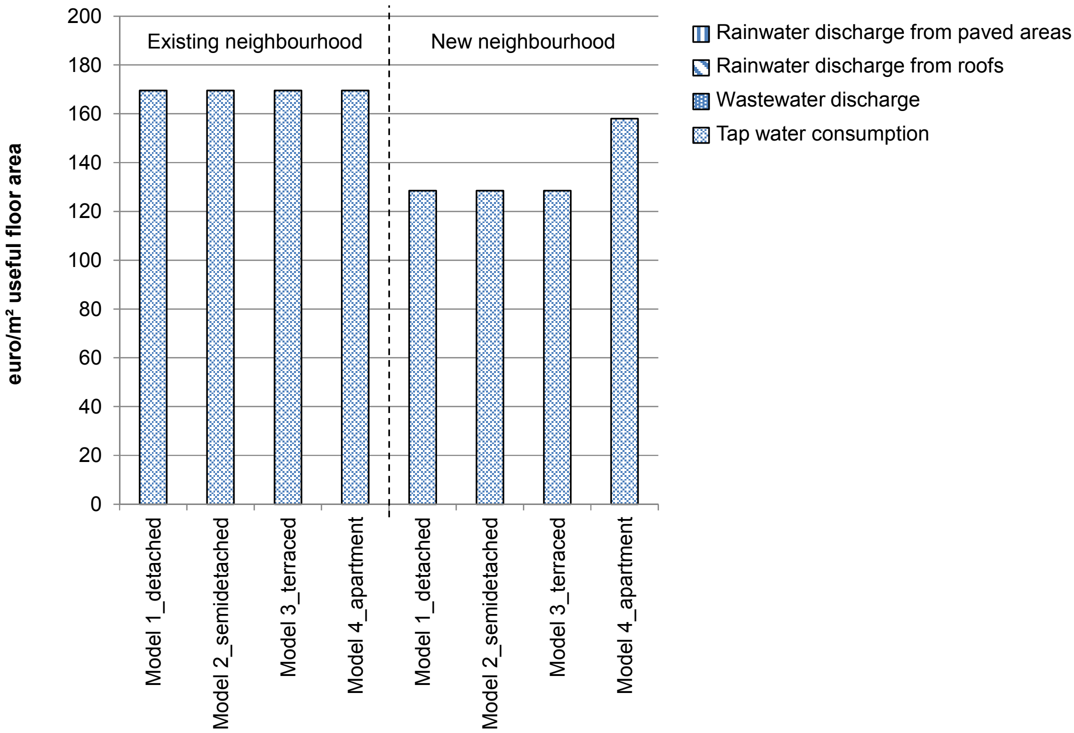

Figure 8.38: Financial cost of operational water use for the reference neighbourhoods, subdivided per contributor.

8.6.3 Water related sustainability measures

Description of the analysed measures

Three sustainability measures related to operational water use are analysed. The first measure focuses on the impact of rainwater reuse by defining a scenario without rainwater tanks (W1_no rainwater tank) which is compared to the reference new variant. As already mentioned in section 8.3.1, the reference new variants include the following rainwater collection tanks: one tank of 5000 litres per building for the models consisting of single-family houses and three tanks of 20000 litres per building for the apartment model.

The second and third sustainability measures consist of alternative scenarios for the rainwater management. Compared to the reference variant (separate sewer and drainage ditches) two systems are analysed (Table 8.13): (1) an 'old' system of combined sewer (W2_combined sewer) and (2) the use of permeable materials for the paved areas (W3_permeable areas). In the last scenario, only a sanitary sewer is provided as the rainwater falling on the paved areas can directly infiltrate into the ground. For the rainwater discharge from roofs, the overflow of the rainwater tanks is connected to drainage ditches[21]. The external elements used in this scenario are summarised in Table 8.14.

[21] The required amount of drainage ditches is very limited as about 80% of the rainwater discharge from roofs is reused in the buildings.

Table 8.13: Technical systems analysed for rainwater discharge.

Parameter	REF_separate sewer	W2_combined sewer	W3_permeable areas
Sewer type	Separate sewer	Combined sewer	Sanitary sewer
Infiltration system	Drainage ditches	-	Water permeable paved areas + drainage ditches

Table 8.14: External elements for the variant composed of water permeable paved areas (W3_permeable areas). The adaptations to the reference new variant are indicated in green/italics.

External element	Composition
(94.11) road	Geotextile – crushed gravel sub-base – *porous lean concrete base* – *concrete paving stones with enlarged joints*
(94.13) footpath	Geotextile – crushed gravel sub-base – *unbound crushed gravel base* – *concrete paving stones with enlarged joints*
(94.14) parking facilities	Geotextile – crushed gravel sub-base – *porous lean concrete base* – *concrete paving stones with enlarged joints*
(94.15) square	Geotextile – crushed gravel sub-base – *porous lean concrete base* – *concrete paving stones with enlarged joints*
(94.22) gardens	Grass and hedges
(95) piped services	*Vitrified clay sanitary sewer* – drainage ditches – drinking water and gas pipes (HDPE)
(96) electrical services	Electric and data cables

Environmental impact

The environmental cost of the measures related to operational water use is shown in Figure 8.39. The environmental costs for both material use and operational water use are considered to analyse any trade-offs between both. Compared to the reference variants, the variants with a combined sewer lead to an increase in total environmental cost, ranging from 7% for the apartment model to 14% for the detached house model. The variants without rainwater tank and with permeable paved areas have an impact similar to the reference variants.

For the variants without a rainwater tank, the impact is similar to the reference variants because the higher environmental cost for tap water consumption is compensated by the lower material environmental cost resulting from the absence of rainwater tanks.

The higher impact of the variants with a combined sewer, compared to the reference variants, is a consequence of the high impact for the treatment of rainwater discharged from paved areas, when rainwater and wastewater are collected in a single sewer pipe. As a result the water environmental cost increases from 32% for the apartment model to 71% for the detached house model. The increase is lower for models with a higher built density due to the lower volume of rainwater discharge (see Figure 8.36). Regarding the material environmental cost, a small impact reduction is obtained for the variants with a combined sewer compared to the reference variants.

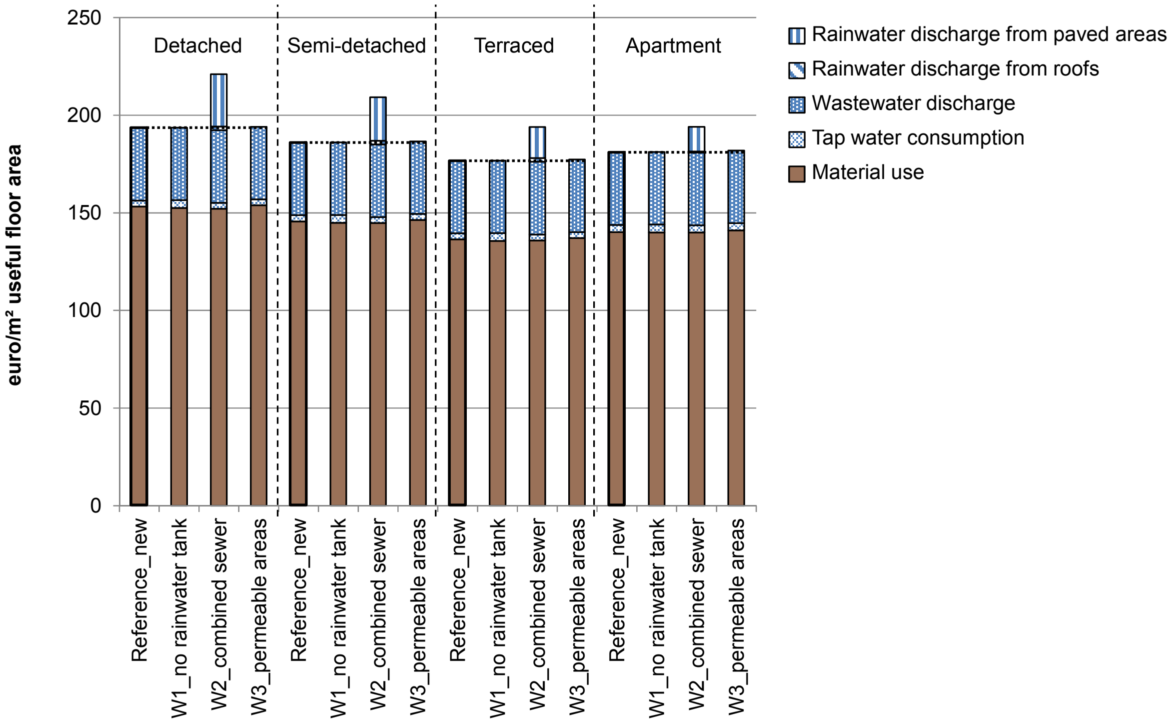

Figure 8.39: Environmental cost of the sustainability measures related to operational water use, applied to the reference new neighbourhoods.

Finally, the variants with permeable paved areas have an environmental cost similar to the reference variants because there is no impact for rainwater discharge in both cases. Furthermore, the material environmental cost is similar to the reference variants because the higher impact of the permeable paved areas is compensated by the lower impact of piped services, as only a sanitary sewer is provided.

Financial impact

The financial cost of the measures related to water use shows that all strategies analysed have an impact similar to the reference variants (Figure 8.40). The reason is the low contribution of operational water use to the financial cost.

As for the environmental cost, the financial cost of the variants without rainwater tank is similar to the reference variants because the higher impact for tap water consumption is compensated by a lower material impact.

Unlike the environmental cost, the variants with a combined sewer do not result in an increase of the financial cost for water use because the cost for wastewater treatment is integrated in the tap water price. As a result, there is no financial incentive for separating wastewater and rainwater flows from each other.

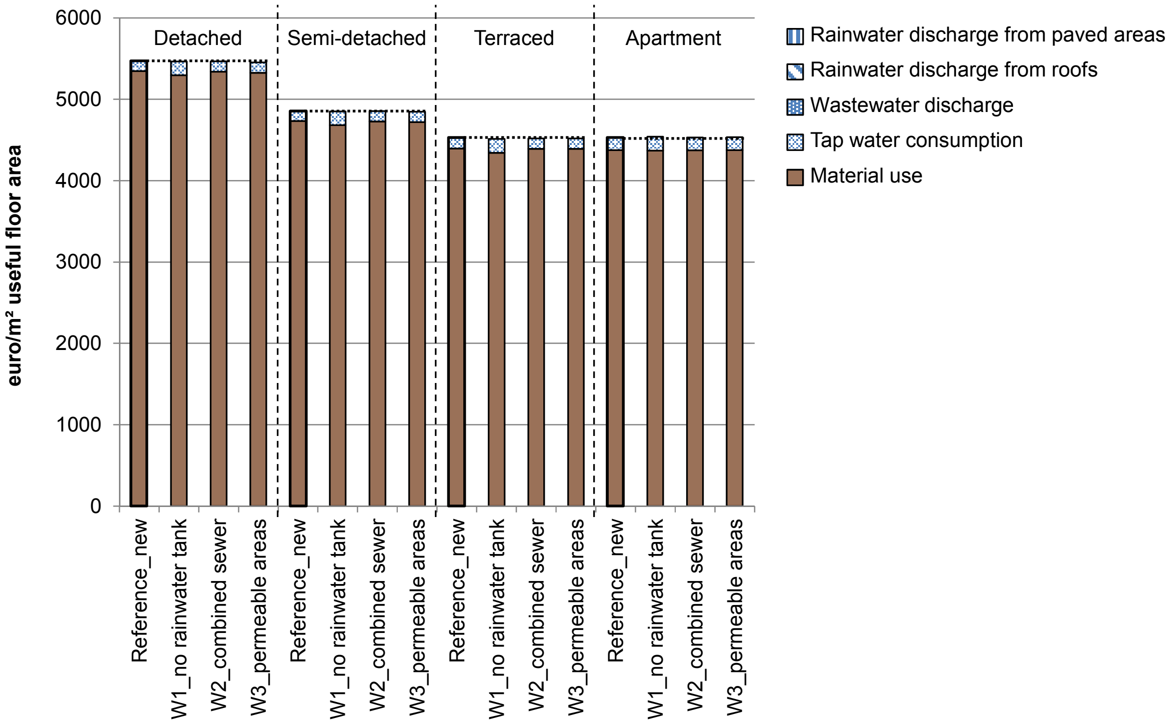

Figure 8.40: Financial cost of the sustainability measures related to operational water use, applied to the reference new neighbourhoods.

Finally, the variants with permeable paved areas have a similar financial impact to the reference variants because there is no change in tap water consumption. As for the environmental cost, the material financial cost is similar to the reference variants because the higher cost of the permeable paved areas is compensated by the lower cost of the piped services.

8.7 Assessment of primary land use

8.7.1 Impact of the monetisation method

As mentioned in Chapter 5, the monetisation of land use impacts on biodiversity in the current MMG method (De Nocker and Debacker 2015) has a number of limitations. First, monetary values are only available for land occupation and not for land transformation. Second, the MMG monetary values are based on impacts expressed in m² and a subdivision in three land use categories: urban, agricultural and forest. The monetary values are therefore not directly linked to the loss of species, calculated in Eco-indicator 99 (Goedkoop and Spriensma 2000).

To tackle this issue, an alternative valuation method was proposed based on the impacts expressed in PDF (Potentially Disappeared Fraction of species). The original and alternative set of monetary values, which are referred to as MMG and MMG_PDF respectively, are described in Chapter 5. In this section, the E-LCA results based on the MMG and MMG_PDF monetary values are compared. For the comparison, the schematic neighbourhood models are simulated based on both a solid and a timber structure to analyse the influence of timber products, which have a higher impact on land use. The building elements used for the solid and timber variants are described in Table 8.6 and Table 8.9 respectively. For the model consisting of apartments, the timber alternatives are only selected for the windows and non-load-bearing internal walls.

The life cycle environmental cost of the neighbourhood models based on both monetisation scenarios is shown in Figure 8.41. The contribution of primary land use to the neighbourhood life cycle impact depends on the built density and varies from 2% in the apartment model to 10% in the detached house model, based on the MMG monetary values. When using the MMG_PDF monetary values, the contribution is higher, ranging from 5% in the apartment model to about 20% in in the detached house model. This is due to the higher valuation of land use impacts in MMG_PDF.

The choice of the monetisation method has also an influence on the comparison between the solid and timber variants. The timber variants have a lower life cycle environmental cost compared to the solid variants based on MMG but a higher life cycle environmental cost based on MMG_PDF. The reason is again the higher valuation of land use impacts in MMG_PDF, which has a higher influence on the environmental cost of wood-based products.

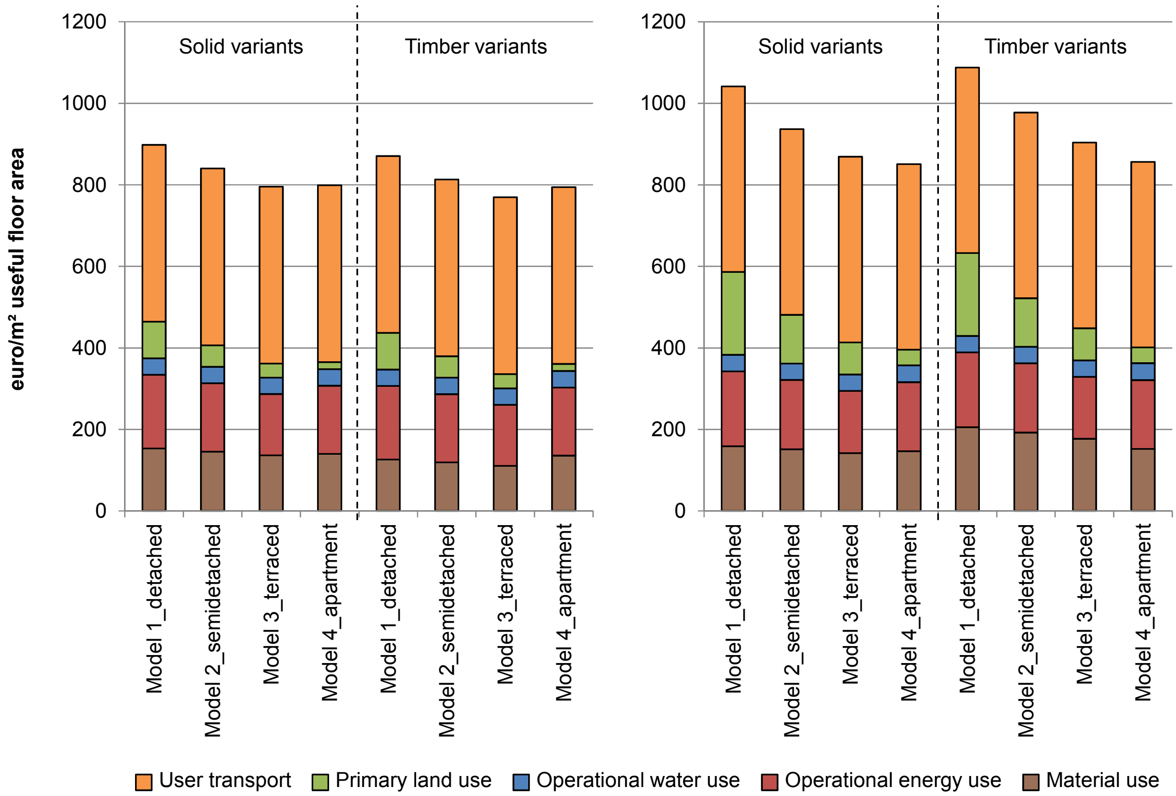

Figure 8.41: Life cycle environmental cost of the neighbourhood models, based on the monetisation scenarios MMG (left) and MMG_PDF (right).

When analysing the impact of primary versus secondary land use (Figure 8.42), the contribution of primary land use to the total land use impact varies from about 30-35% for the apartment model to 60-75% for the detached house model. The impact of secondary land use for the timber variants is highly influenced by the monetisation method. Based on the MMG monetary values, the environmental cost of secondary land use for the timber variants is about 10% higher compared to the solid variants. Based on the MMG_PDF monetary values, the variations are much higher, i.e. about 2 times higher than for the solid variants[22]. The reason for the lower contribution of wooden products based on the MMG monetary values, is the high valuation of urban land use, compared to agricultural and forest land use. In MMG, the monetary value of "land use occupation, biodiversity, urban" is 1364 times higher than for "land use occupation, biodiversity, forest", while the loss of species for urban land use (discontinuously built) is only 9 times higher than for forest land use.

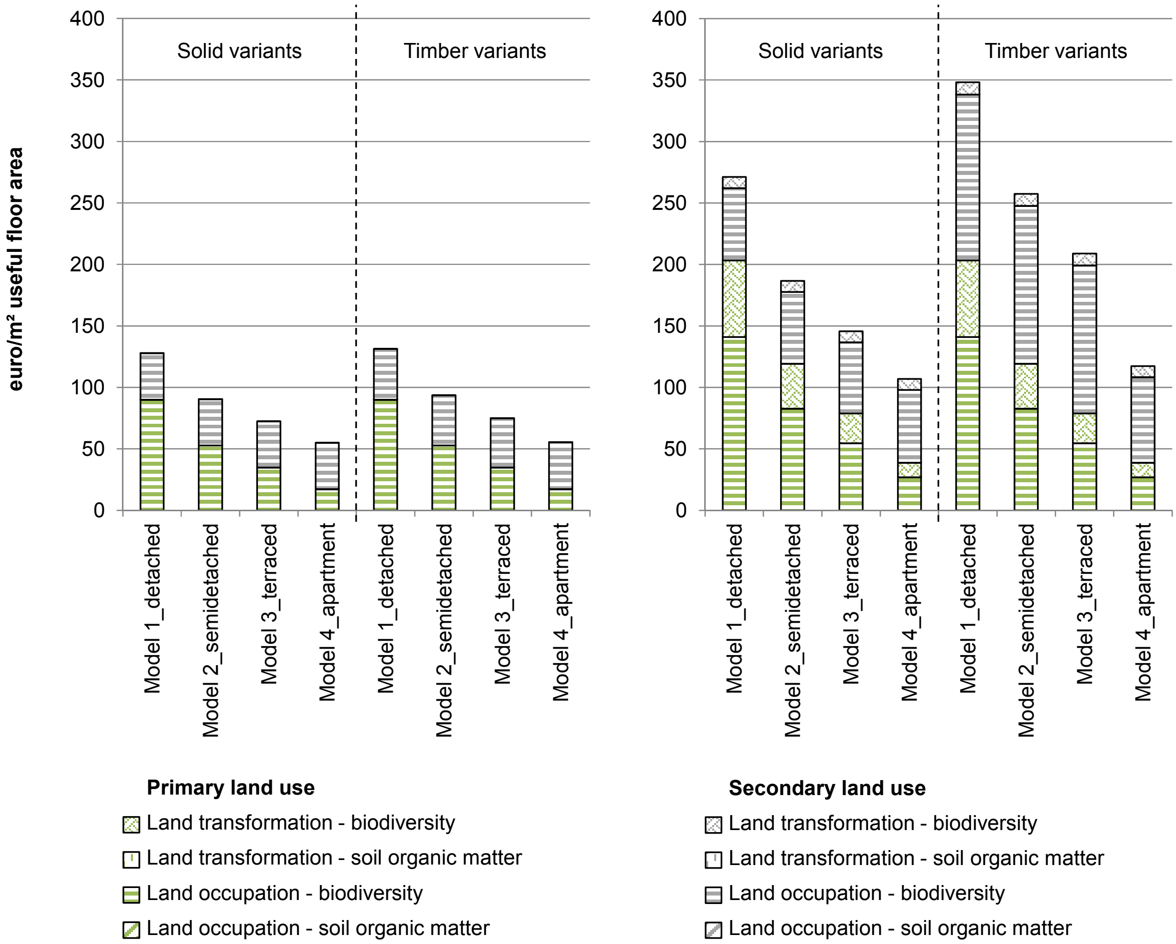

Figure 8.42: Land use environmental cost of the neighbourhood models, subdivided per impact indicator and based on the monetisation scenarios MMG (left) and MMG_PDF (right).

[22] The variations are much smaller for the model consisting of apartments because timber products are only used for the windows and non-load-bearing internal walls.

Regarding the contribution of the land use impact indicators (Figure 8.42), "Land use occupation, biodiversity" is the highest contributor to the land use environmental cost, i.e. more than 99% and from 75 to 85%, based respectively on the MMG and MMG_PDF monetary values. The contribution of the indicator soil organic matter is negligible in all cases. Although "Land use transformation, biodiversity" is not valuated in MMG, it contributes from 15% to 25% of the land use environmental cost, based on MMG_PDF.

8.7.2 Impact of the building land prices

As mentioned in Chapter 5, the building land prices in Flanders can vary significantly depending on the municipality. Therefore a sensitivity analysis is done by comparing the results based on the median value for the building land prices (185.54 €/m²) with the ones based on the first quartile (147.97 €/m²) and third quartile values (235.63 €/m²) (Figure 8.43). The building land prices have a bigger influence on the neighbourhood models with a lower built density. Compared to the median value, the life cycle financial cost of the detached house model is 2% lower based on the first quartile value and 3% higher based on the third quartile value. For the apartment model, the variations do not exceed 1%. As a result, the variations between the neighbourhood models increase when higher building land prices are considered. While the life cycle cost of the apartment model is 17% lower compared to the detached house model based on the first quartile and median values, this reduction increases up to about 21% based on the third quartile value.

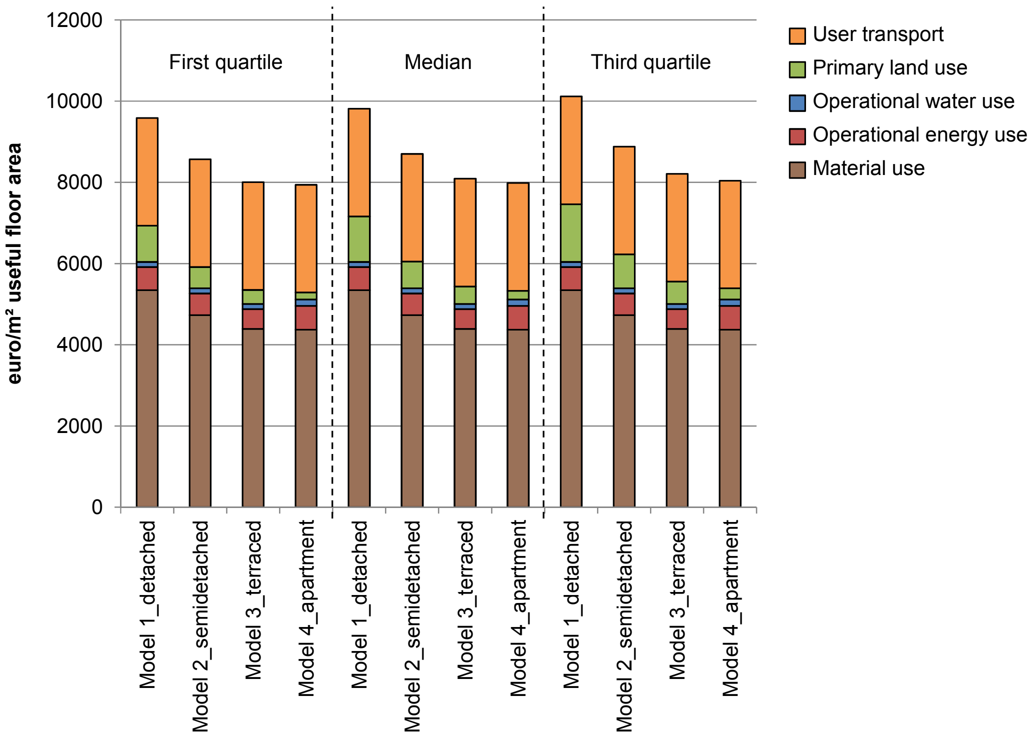

Figure 8.43: Life cycle financial cost of the neighbourhood models, based on the quartile values of the average building land price in Flemish municipalities.

8.7.3 Contributors to the impact of primary land use

Environmental impact

The environmental cost of primary land use, subdivided per contributor, is shown in Figure 8.44. There is no distinction between the existing and new neighbourhoods as the same land use scenarios are applied in both cases. High variations are noticed depending on the built density: the land use environmental cost of the apartment model is about 80% lower than of the detached house model. This is a consequence of the high reduction of the land use impact from gardens and road infrastructure.

When analysing the contributors to the environmental cost of primary land use, the contributions are proportional to the land use ratio’s (Table 8.2), as the same types of original land use (forest land) and neighbourhood land use (urban discontinuously built) are assumed for the buildings, road infrastructure and open spaces. For the models consisting of single-family houses, the main contributor is the land use from gardens (about 40-65% of the land use environmental cost), followed by the road infrastructure (about 15%-20%) and the building footprints (about 10%-25%). The order differs for the apartment model, where the land use from the square (about 30% of the land use environmental cost) is the main contributor, followed by the gardens (about 25%). The contribution of the building footprints, road infrastructure and parking facilities is in this case about 15%.

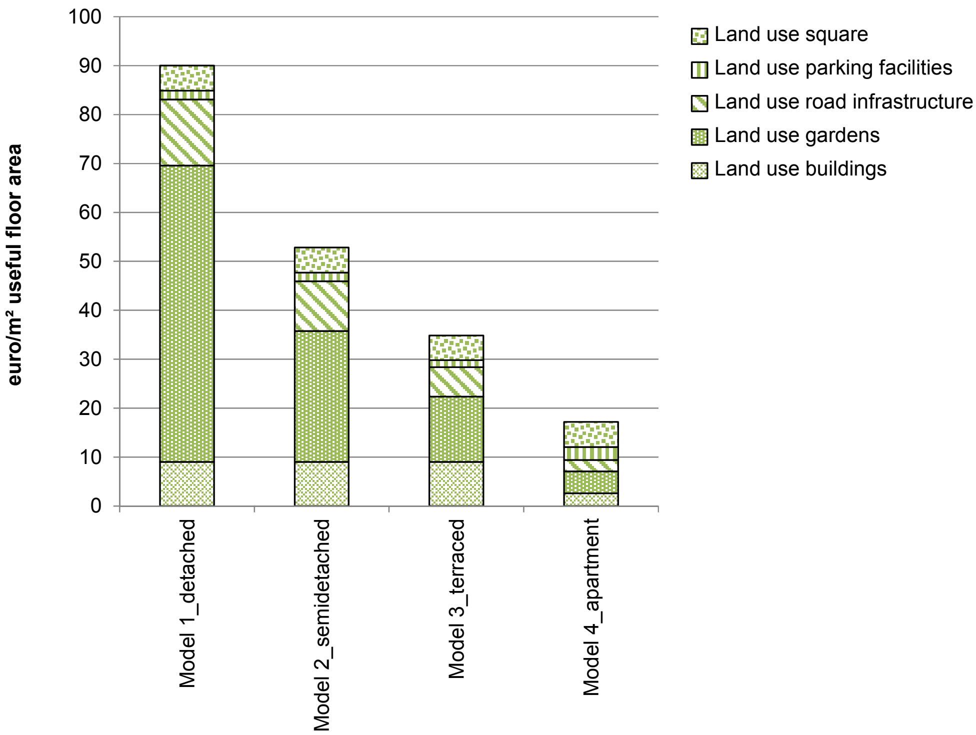

Figure 8.44: Environmental cost of primary land use for the reference neighbourhoods, subdivided per contributor.

Financial impact

The same picture as for the environmental cost is obtained for the financial cost (Figure 8.45) because the financial cost is also proportional to the land use ratios. The observations formulated above are therefore also applicable to the financial cost.

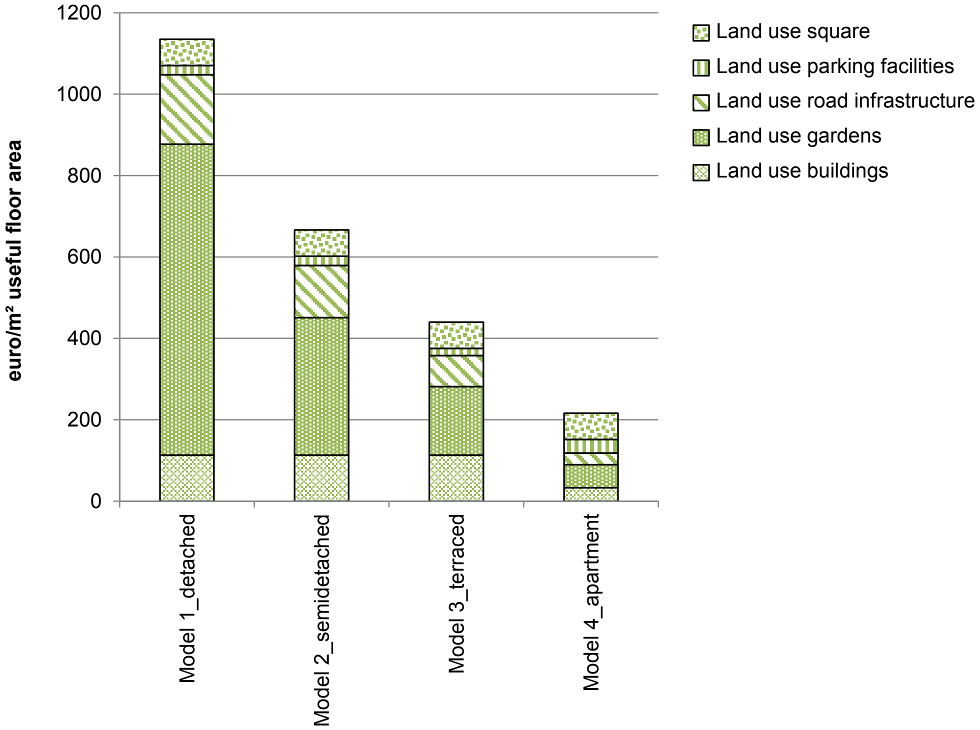

Figure 8.45: Financial cost of primary land use for the reference neighbourhoods, subdivided per contributor.

8.7.4 Land use related sustainability measures

Description of the analysed measures

Three strategies to reduce the impact of primary land use are analysed. The first two measures focus on the original type of land use by analysing the effect if the neighbourhood is developed on urban land (L1_urban land) or arable land (L2_arable land) instead of forest land. In the third measure, the central public square is replaced by a park (L3_park) characterised by the land use type “urban, green areas”.

Environmental impact

The environmental cost of the sustainability measures related to primary land use is calculated based on both the MMG and MMG_PDF monetary values (Figure 8.46 and Figure 8.47). The environmental cost for both material and primary land use is considered as the third sustainability measure has an impact on both.

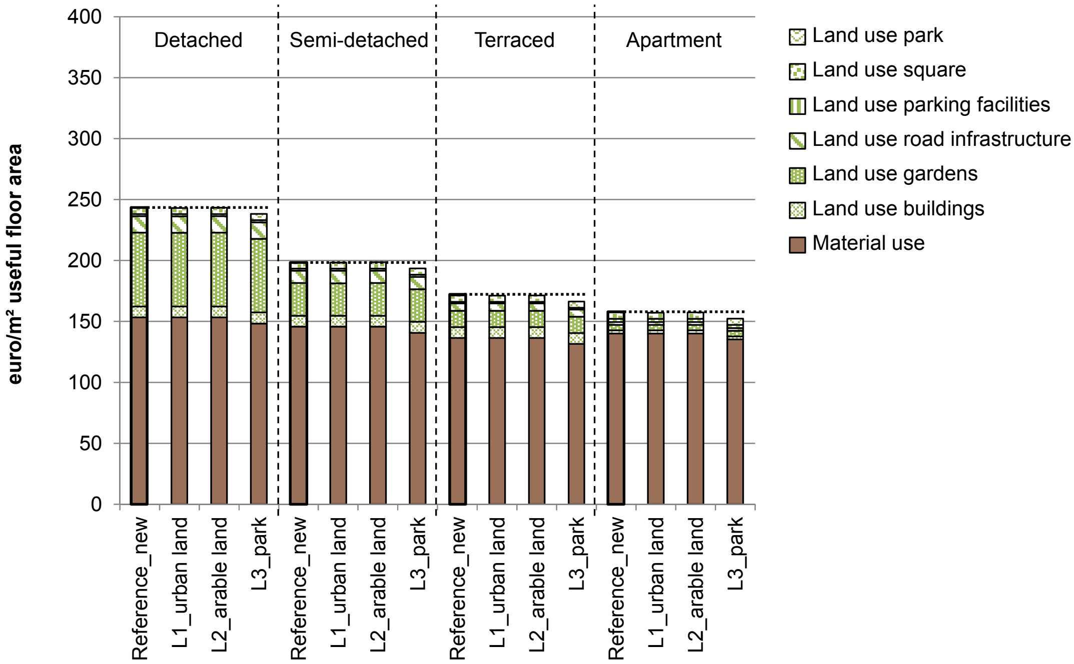

Figure 8.46: Environmental cost of the sustainability measures related to primary land use, applied to the reference new neighbourhoods (MMG monetary scenario).

The results based on the MMG monetary values (Figure 8.46) show limited impact variations. While the urban land and arable land variants have an impact similar to the reference variants, the park variants lead to a small environmental cost reduction of 2-3%.

For the first two strategies (L1_urban land and L2_arable land), the environmental impact is similar to the reference variants because biodiversity impacts related to land transformation are not assessed based on the MMG monetary values.

The slightly lower environmental cost of the park variants is due to a reduction of 3-4% of the environmental material cost. Compared to a square, the environmental impact of green areas is assumed to be zero due to a lack of data on the impact of the cultivation of trees and plants (see Chapter 7). Regarding primary land use, the environmental cost of the park variants is similar to the reference variants because the MMG valuation of biodiversity impacts related to land occupation is based on three main land use categories (urban, agricultural and forest land use) and does not make a distinction between the land use types “urban, discontinuously built” and “urban, green areas”.

The results based on the MMG_PDF monetary values (Figure 8.47) show higher environmental cost reductions compared the reference variants. The highest impact reductions are obtained for the arable land variants (from 8% to 21% for the model consisting of apartments and detached houses respectively), followed by the urban land variants (from 6% to 17%). The reductions are higher for the neighbourhood models with a lower built density due to the higher contribution of primary land use in these models. For the park variants the impact reductions are limited to 2-3%.

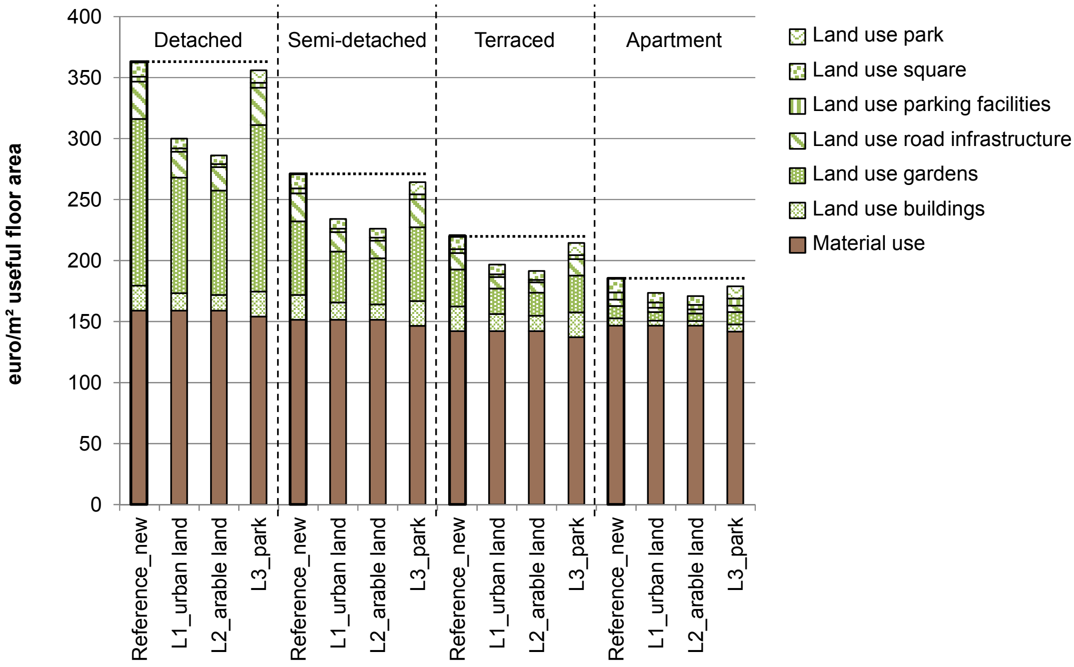

Figure 8.47: Environmental cost of the sustainability measures related to primary land use, applied to the reference new neighbourhoods (MMG_PDF monetary scenario).

The lower impact of the urban land and arable land variants compared to the reference variants is a result of the reduction of the environmental cost of primary land use by respectively 31 and 37%. The reduction is higher for the arable land variants because the conversion from arable land to urban land leads to a negative environmental cost for the indicator “Land, transformation, biodiversity”. This is a consequence of the higher number of species for a discontinuously built urban land compared to arable land.

The lower impact of the park variants compared to the reference variants is a result of the 13% lower land use impact for a park compared to a square. However this reduction has a limited influence on the environmental cost of primary land use due to the relatively small contribution of the square to the land use impacts. Next to the reduction of the primary land use impact, the material environmental cost is reduced by about 3%. This is again a consequence of the environmental impact of green areas which is assumed to be zero.

Financial impact

The financial cost of the sustainability measures (Figure 8.48) reveal low variations compared to the reference variants. The reason is that building land prices are only dependent on the location and not on the type of (original) land use. As a result, the total financial cost of the first two strategies (L1_urban land and L2_arable land) is identical to the reference variants. For the park variants, a small cost reduction of 1% is obtained. This reduction results from the lower material cost for a park compared to a square.

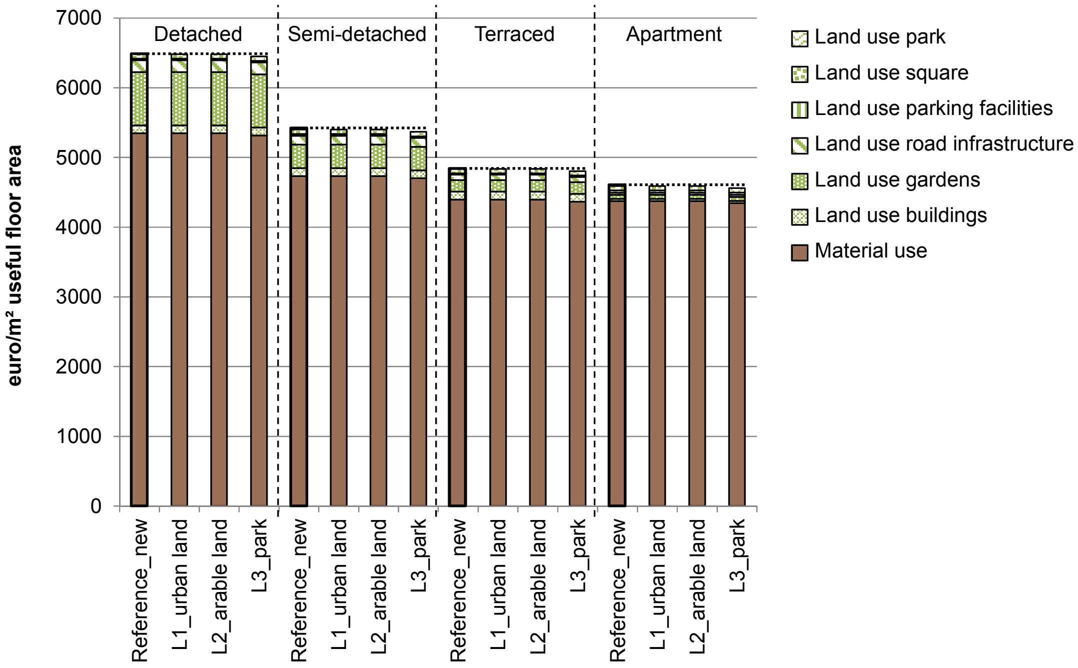

Figure 8.48: Financial cost of the sustainability measures related to land use, applied to the reference new neighbourhoods.

8.8 Assessment of user transport

8.8.1 Contributors to the impact of user transport

Environmental impact

The analysis of the contributors to the impact of user transport (Figure 8.49) reveals that car transport contributes to 96% of the environmental cost of the reference transport profile. This high contribution is due to the long transport distances by car and the high environmental cost per person-kilometre (pkm) compared to other transport modes (see Chapter 5).

Next to the reference transport profile, the influence of two parameters is investigated (Figure 8.49). First, an increase of the car occupancy rate is analysed. The average car occupancy in Flanders, which equals 1.8 person per vehicle (Declercq et al. 2016), is quite low and could be increased by stimulating carpooling. The analysed scenario focuses on an higher occupancy rate of 3 people which corresponds to the minimum occupancy rate for the use of carpool lanes (Taxistop 2016). Compared to the reference transport profile, this scenario leads to a reduction of 33% of the environmental cost of user transport. Second, the use of electric cars instead of petrol and diesel cars is analysed. In this case an impact reduction of 18% is obtained compared to the reference transport profile.

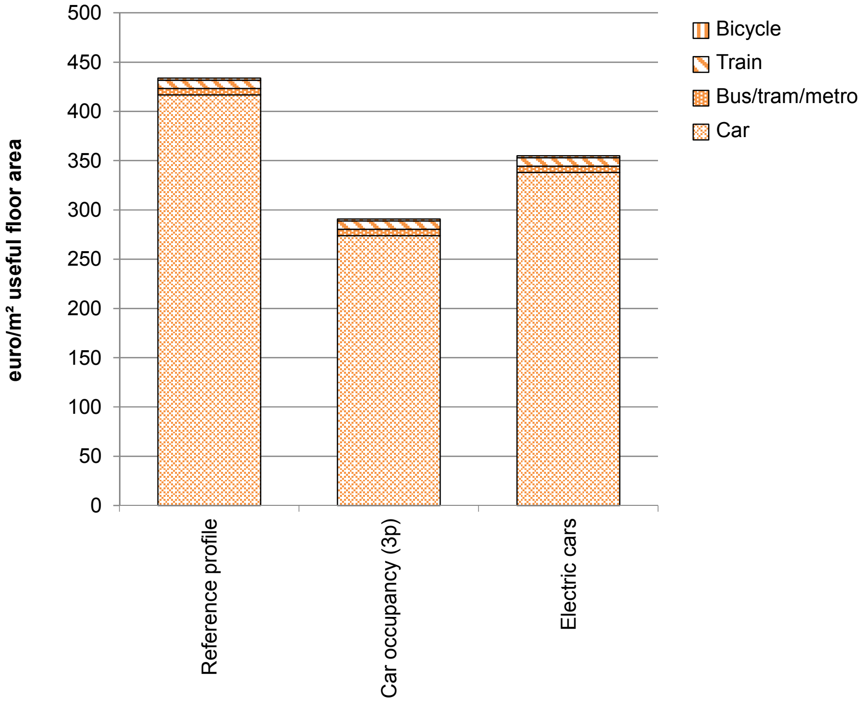

Figure 8.49: Environmental cost of user transport. Besides the reference transport profile, the impact of an increased car occupancy of three people and the use of electric cars is shown.

Financial impact

The analysis of the financial cost of user transport (Figure 8.50) shows again the high contribution of car transport (96% of the financial cost for the reference transport profile). The reasons are again the high contribution of car transport to the total transport distances and the high financial cost per pkm, compared to other transport modes (see Chapter 5).

Regarding the alternative scenarios, the increased occupancy rate of 3 people leads to a reduction of 38% of the financial cost compared to the reference transport profile. Unlike the environmental cost, the use of electric cars results in a cost increase of 28% due to the higher investment cost of electric cars compared to petrol and diesel cars.

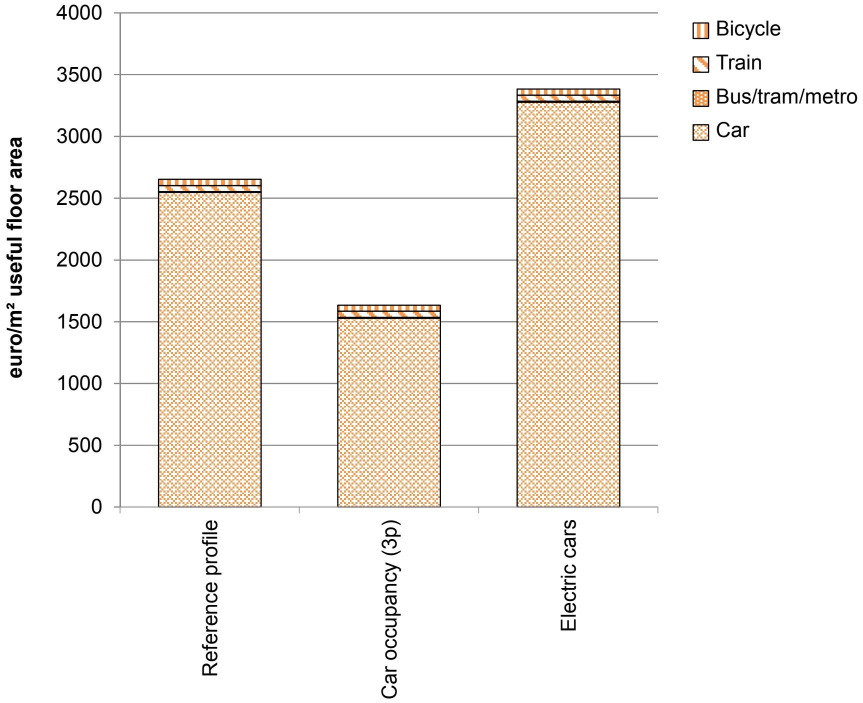

Figure 8.50: Financial cost of user transport. Besides the reference transport profile, the impact of an increased car occupancy of three people and the use of electric cars is shown.

8.8.2 User transport related sustainability measures

Description of the analysed measures

Three sustainability measures related to user transport are analysed. The first two measures investigate the impact of the neighbourhood location. Both a location in an urban area (T1_urban area) and a rural area (T2_rural area) are analysed. For the urban area, the schematic neighbourhood models are assumed to be built in Leuven. The transport profile "Regional urban area - central municipalities" (see Chapter 5) is selected to characterize the transport of the inhabitants. Furthermore the average building land price for Leuven (282.63 euro/m²) is assumed instead of the Flemish average (187.79 €/m²). For the rural area, a location in Rotselaar, a municipality near Leuven, is considered. The related transport profile ("Rural area") and building land price for Rotselaar (187.28 euro/m²) are assumed.

The third sustainability measure focuses on the impact of the cycling infrastructure, including the provision of bicycle paths in the whole neighbourhood. The bicycle paths are 1.75 metres wide and integrated on both sides of the roads. A surface layer in red concrete paving stones is considered. The impact of the cycling infrastructure on the reference transport profile is estimated based on the method described in Chapter 5 and reported in Table 8.15.

Table 8.15: Calculation of the site specific transport profile for the sustainability measure related to the cycling infrastructure (T3_bicycle path).

	Car	Bicycle	On foot	Public transport
Reference transport profile Flanders (km/person/day)	31.17	1.92	0.55	2.92
Good link to bicycle network	-8%	+10%	-10%	-5%
Cycle friendly neighbourhood	-1%	+9%	-3%	-13%
Total correction terms	**-9%**	**+19%**	**-13%**	**-19%**
Site specific transport profile (km/person/day)	**28.33**	**1.69**	**0.48**	**2.38**

Environmental impact

The environmental cost of the strategies related to user transport is shown in Figure 8.51. The environmental cost for material use, operational energy use, primary land use and user transport is considered as the analysed measures have an impact on these various drivers. Compared to the reference variants, the urban area and bicycle path variants lead to a reduction of the total environmental cost of 10-11% and 3-5% respectively. The variants located in a rural area result in an environmental cost increase of 6-7%.

The lower impact of the variants located in an urban area compared to the reference variants is a result of the reduction of the user transport environmental cost by 20%. This reduction is mainly due to the lower car transport distances in urban areas.

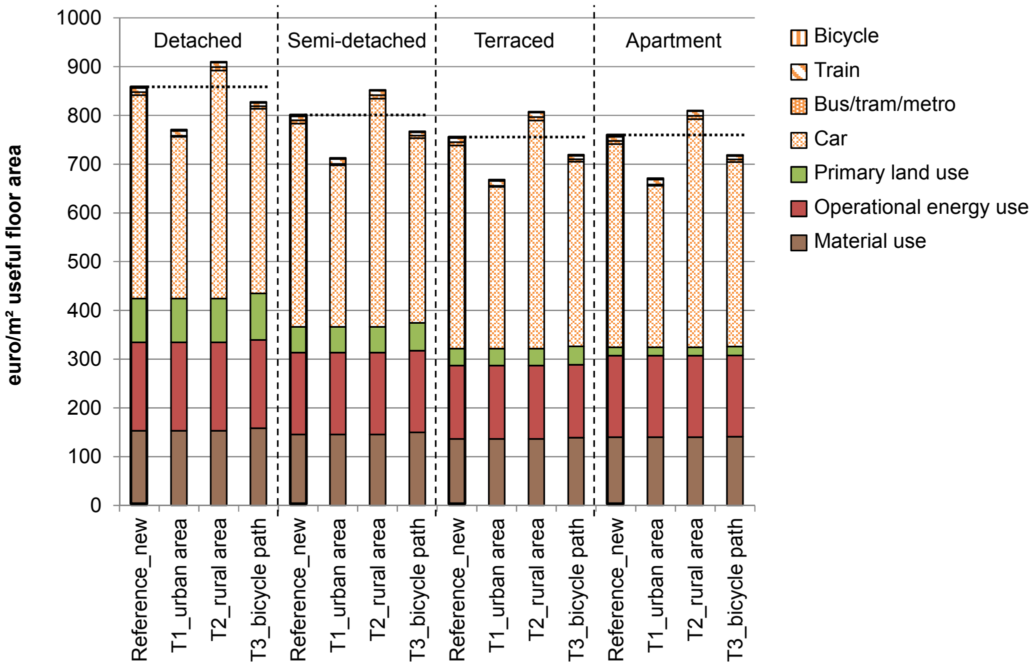

Figure 8.51: Environmental cost of the sustainability measures related to user transport, applied to the reference new neighbourhoods.

Contrariwise, the higher impact of the rural area variants compared to the reference variants is a consequence of the increase of the user transport environmental cost by 12%, resulting from the higher car transport distances in rural areas.

Finally, the small impact reduction for the bicycle path variants is a result of the reduction of the user transport environmental cost by 9% compared to the reference variants. However, this reduction is partially compensated by an impact increase of 6-8% for primary land use, resulting from the additional land use area required for the cycling infrastructure. The environmental material cost also increases by 1-3% as a result of the construction and maintenance of the bicycle paths. Furthermore, the influence of the wider streets on the solar gains in buildings and energy use for road lighting is considered but has a negligible impact on the operational energy cost.

Financial impact

The financial cost of the sustainability measures shows lower variations compared to the environmental cost. The reason is the lower contribution of user transport to the financial impact. Compared to the reference variants, the variants located in an urban area lead to a reduction of the total financial cost of 2-5% for the model consisting of semi-detached, terraced houses and apartments. The financial impact increases by 1% for the model consisting of detached houses. This is a consequence of the higher influence of higher building land prices on models with a lower built density. For the bicycle path variants, the financial cost reduction is limited to 1-3%. For the rural area variants, a cost increase of 3-4% is obtained compared to the reference variants.

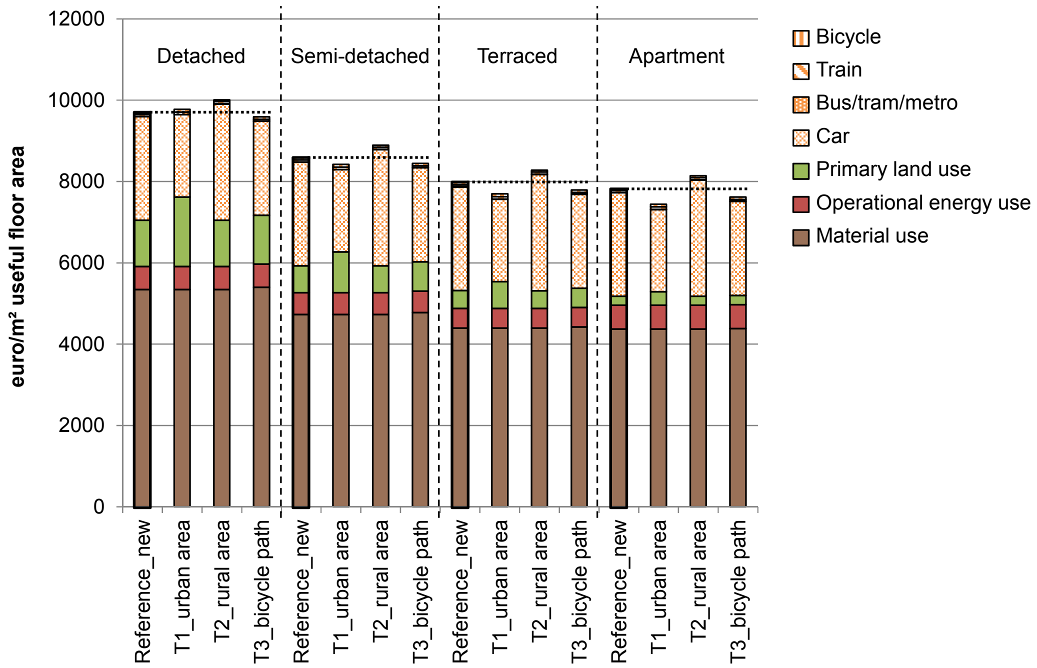

Figure 8.52: Financial cost of the sustainability measures related to user transport, applied to the reference new neighbourhoods.

The impact of the urban area variants can be explained by the reduction of the user transport cost by 19%, which is partially or completely compensated by the increase of the primary land use cost by 51%, resulting from the higher building land prices in Leuven.

The higher cost of the rural area variants compared to the reference variants is a result of the increase of the user transport cost by 12%. The financial cost for primary land use is similar to the reference variants, as the average building land price in Rotselaar is almost equal to the Flemish average.

As for the environmental cost, the small financial cost reduction for the bicycle path variants compared to the reference variants is a result of the reduction of the user transport cost by 9%, which is partially compensated by the increase of the primary land use (+6-8%) and material cost (+1%). The impact of the wider streets on the operational energy cost is again negligible.

8.9 Conclusions

In this chapter the integrated life cycle approach is used to assess a number of schematic neighbourhood models with various layouts and built densities. Two types of analysis are done: an overall analysis based on two reference variants, representative for existing and newly built neighbourhoods and a detailed analysis per impact driver, including the assessment of a number of sustainability measures. The conclusions related to both analyses are reported in the subsequent sections.

8.9.1 Conclusions related to the analysis of the reference variants

Four main conclusions can be formulated based on the assessment of the reference variants. First, the new construction standards reveals high impact reductions compared to the existing standards with a reduction of about 60% and 20% for the life cycle environmental and financial cost respectively. The main reason is the reduction of the impact of operational energy use, resulting from the stricter energy performance requirements in new buildings.

Second, the urban form and built density have a high influence on the life cycle environmental and financial cost. Compared to the detached house model, the life cycle environmental cost of the model consisting of apartments is about 45% and 10% lower for the existing and new variants respectively. The same applies to the life cycle financial impact with cost reductions of about 30% and 20% respectively. Based on the analysis of the contributors, four main reasons are identified for these variations. First, the built density and compactness have a high influence on the energy demand for heating, which is a major contributor to the impact of energy use. Second, a higher built density results mostly in a lower material use for buildings, networks and open spaces due to lower element ratios. Third, the impact of primary land use decreases significantly for higher built densities. Finally, the volume of rainwater discharged from roofs and paved areas is higher in models with a low built density. However, this parameter has only an influence on the life cycle environmental cost of the existing neighbourhood variants, where a combined sewer is implemented.

Despite the positive influence of the urban form and built density, the reductions tend to flatten for high built densities, especially for the new neighbourhood variants where the life cycle costs of the apartment model are similar to the terraced house model. Two reasons are identified. First, there is a lower potential for PV electricity production in the apartment model due to the lower roof ratio. Second, the impact of material use in apartment buildings is similar to the terraced houses due to the additional impact of collective circulation spaces and the high impact of pile foundations.

Third, the analysis of the impact drivers shows the importance of material use, operational energy use and user transport, which contribute together to more than 85% of the life cycle financial and environmental cost of neighbourhoods. Their relative contribution however varies importantly depending on the construction standards as the impact of operational energy use is much higher in the existing variants. Furthermore, variations are noticed between the financial and environmental impact assessment as material use is the main contributor to the life cycle financial cost but a much lower contributor to the life cycle environmental cost. On the other hand the contribution of primary land use and operational water use to the life cycle financial and environmental cost do not exceed 10% in most cases. Nevertheless, the contribution of primary land use to the life cycle environmental cost depends on the selected monetisation method. Based on the alternative monetisation scenario MMG_PDF, higher impact contributions, up to 20% for the detached house model, are obtained. The same applies to the financial cost of primary land use as building land prices can vary importantly depending on the location.

Finally, regarding the contribution of the life cycle modules, the use stage is the main contributor to the life cycle financial and environmental cost with a contribution of 70-80% and 90-95% respectively. This results from the high impact of operational energy use and user transport but also from the cleaning activities in the case of the financial cost. Besides the use stage, the contribution of the before use stage to the life cycle financial cost is not negligible (about 15-30%).

8.9.2 Conclusions related to the analysis of the sustainability measures

Various sustainability measures related to material use, operational energy use, operational water use, primary land use and user transport have been assessed. The life cycle impacts of these measures are summarised in Figure 8.53. Four main conclusions can be formulated.

	Detached			Semi-detached			Terraced			Apartment		
	LCC	E-LCA	TOT	FIN	ENV	TOT	FIN	ENV	TOT	FIN	ENV	TOT
MMG monetisation												
Reference_new (€/m²)	9.8E+03	9.0E+02	1.1E+04	8.7E+03	8.4E+02	9.6E+03	8.1E+03	8.0E+02	8.9E+03	8.0E+03	8.0E+02	8.8E+03
M1_timber	+10%	-3%	+9%	+7%	-3%	+6%	+3%	-3%	+2%	-1%	-1%	-1%
M2_recycled materials	+2%	-1%	+2%	+2%	-1%	+2%	+1%	-1%	+1%	+1%	-1%	+1%
E1_non-insulated	+9%	+40%	+11%	+8%	+37%	+11%	+7%	+32%	+9%	+3%	+15%	+4%
E2_passive standard	-0%	-7%	-1%	-0%	-7%	-1%	-0%	-6%	-1%	+0%	-4%	-0%
E3_oil boiler	+4%	+31%	+6%	+4%	+30%	+7%	+4%	+27%	+6%	+3%	+21%	+5%
E4_heat pump	+2%	-3%	+2%	+3%	-3%	+2%	+3%	-2%	+2%	+2%	-2%	+2%
E5_no PV	+2%	+5%	+2%	+2%	+6%	+2%	+2%	+6%	+2%	+0%	+2%	+1%
W1_no rainwater tank	-0%	+0%	-0%	-0%	+0%	-0%	-0%	+0%	-0%	+0%	+0%	+0%
W2_combined sewer	-0%	+3%	+0%	-0%	+3%	+0%	-0%	+2%	+0%	-0%	+2%	+0%
W3_permeable areas	-0%	+0%	-0%	-0%	+0%	-0%	-0%	+0%	-0%	+0%	+0%	+0%
L1_urban land	0%	-0%	-0%	0%	-0%	-0%	0%	-0%	-0%	0%	-0%	-0%
L2_arable land	0%	-0%	-0%	0%	-0%	-0%	0%	-0%	-0%	0%	-0%	-0%
L3_park	-0%	-1%	-0%	-0%	-1%	-0%	-0%	-1%	-0%	-0%	-1%	-0%
T1_urban area	+1%	-10%	-0%	-2%	-10%	-3%	-3%	-11%	-4%	-5%	-11%	-5%
T2_rural area	+3%	+6%	+3%	+4%	+6%	+4%	+4%	+7%	+4%	+4%	+7%	+4%
T3_bicycle path	-1%	-3%	-1%	-2%	-4%	-2%	-2%	-4%	-2%	-3%	-5%	-3%
MMG_PDF monetisation												
Reference_new (€/m²)	9.8E+03	1.0E+03	1.1E+04	8.7E+03	9.4E+02	9.6E+03	8.1E+03	8.7E+02	9.0E+03	8.0E+03	8.5E+02	8.8E+03
L1_urban land	0%	-6%	-1%	0%	-4%	-0%	0%	-3%	-0%	0%	-1%	-0%
L2_arable land	0%	-7%	-1%	0%	-5%	-0%	0%	-3%	-0%	0%	-2%	-0%
L3_park	-0%	-1%	-0%	-0%	-1%	-0%	-0%	-1%	-0%	-0%	-1%	-0%

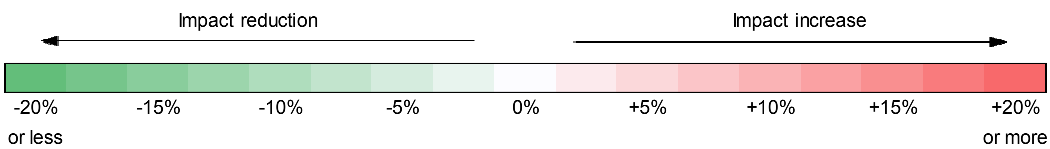

Figure 8.53: Life cycle impacts (financial (LCC), environmental (E-LCA) and total (TOT)) of the sustainability measures analysed. The results are expressed as a percentage compared to the reference new neighbourhoods. Impact increases and reductions are indicated with a red to green colour scale.

First, as can be seen from the colour scale (Figure 8.53), the highest impact variations compared to the reference variants are obtained for strategies related to operational energy use (E1, E2, E3), user transport (T1, T2) and material use (M1), which are also the main contributors to the life cycle impacts. Measures related to primary land use and operational water use result in small impact variations, never exceeding 3%. For the primary land use strategies, higher environmental cost variations are however obtained when the MMG_PDF monetisation scenario is applied.

When focusing on the life cycle financial results, impact variations compared to the reference variants do not exceed 10%. Increases of more than 5% are obtained for the timber variants and non-insulated variants. None of the strategies lead to financial impact reductions of more than 5%. For the environmental results, the impact variations are much higher, i.e. up to 40% compared to the reference variants. Increases in life cycle environmental cost of more than 5% are obtained for the following measures: E1_non-insulated, E3_oil boiler, E5_no PV and T2_rural area. Impact reductions of more than 5% are obtained for the passive variants and variants located in an urban area. Regarding the total cost, a similar picture to the financial cost is obtained due to the low contribution of the environmental cost to the total cost.

Second, the influence of the sustainability measures can vary importantly for the financial and environmental impact, as some strategies have an opposite effect on both. For example the timber variants and heat pump variants lead to a lower life cycle environmental cost but a higher life cycle financial cost compared to the reference variants.

Third, the effect of some sustainability measures varies depending on the built density. For example, the influence of the energy performance level (“E1_non-insulated” and “E2_passive”) is higher on buildings with a lower compactness. Another example is the PV-system which has a lower effect for the apartment model due to a lower roof ratio.

Finally, the detailed analysis of each sustainability measure reveals the importance of considering the trade-offs between the various drivers. For example, the decrease of the operational energy cost of the passive variants is (partially) compensated by the increase of the material cost resulting from the higher insulation levels and improved ventilation system. Another example is the provision of bicycle paths where the reduction of the cost for user transport is partially compensated by the higher cost for primary land use and material use.

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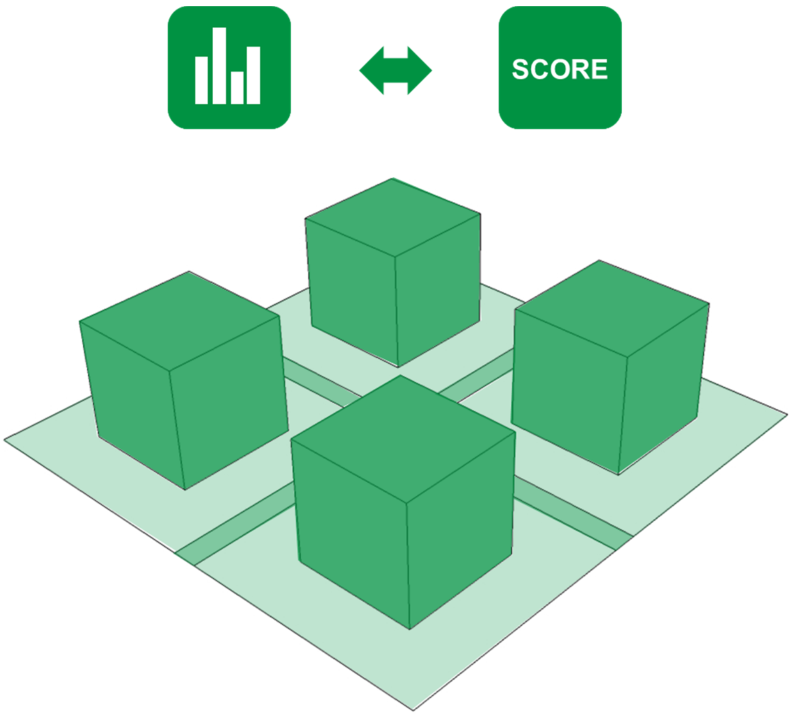
CHAPTER 9

Comparison between the scoring tools and the life cycle approach

In this chapter, scoring tools for neighbourhoods are compared with the integrated life cycle approach developed in this PhD research. The objective is to analyse the effectiveness of scoring tools in assessing the sustainability of neighbourhoods. For each schematic neighbourhood model defined in Chapter 8, the life cycle impacts and qualities resulting from various sustainability measures are compared with the scores awarded in BREEAM Communities, DZM Wijken, and DGNB New Urban Districts. Based on the comparison, convergences and divergences are highlighted and recommendations for methodological improvements are formulated.

The preliminary results of this study, focusing only on one neighbourhood model and covering a limited set of sustainability measures, are published in a conference paper (Trigaux et al. 2016).



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9.1 Introduction

The objective of this chapter is to make a comparison between scoring tools and the developed life cycle approach. Despite the large number of assumptions and uncertainties related to E-LCA and LCC, the developed life cycle approach provides a transparent framework to critically analyse the methodology of scoring tools, which lack scientific base and are rather characterized by their black box nature.

In a previous research (Humbert et al. 2006), a critical evaluation of the scoring system LEED was carried out. This research consisted of an E-LCA analysis of LEED credits, applied to a specific office building. The study revealed discrepancies between the rating levels and their actual environmental impact.

In this dissertation, the critical evaluation focuses on scoring tools for neighbourhoods. The analysis is based on various sustainability measures, which are applied to four schematic neighbourhood models, composed of respectively detached houses, semi-detached houses, terraced houses and apartments (see Chapter 8). The sustainability measures consist of strategies related to material use, operational energy use, operational water use, primary land use and user transport. Not only the environmental impact of the strategies but also the financial consequences and the impact on the neighbourhood qualities are evaluated in this chapter.

The life cycle impacts and qualities of the sustainability measures are then compared with the scores awarded in three scoring tools for neighbourhoods. The selected tools include BREEAM Communities (version 2012) (BRE 2016) and “Duurzaamheidsmeter Wijken” (DZM Wijken) (Flemish Government 2017), which are the most used in the Belgian context[1]. Moreover, the tool DGNB New Urban Districts (version 2012) (DGNB GmbH 2012)[2] is also considered, as it integrates a number of criteria based on E-LCA and LCC.

9.2 Life cycle impacts and qualities of sustainability measures

The life cycle financial and environmental impacts of the analysed sustainability measures are described in detail in Chapter 8. Concerning the quality assessment, the positive or negative impact of each sustainability measure is reported in Figure 9.1. The assessment is based on the framework elaborated in Chapter 5. As quality scores and weighting are not defined in this research (see Chapter 5), only a plus or minus symbol is attributed to the various quality aspects.

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[1] The tool developed by Vandevyvere (Vandevyvere 2010) is not included in the critical analysis as it is still a research tool and therefore not yet used in the Belgian building sector.

[2] Recently, an updated German version of DGNB New Urban Districts has become available (DGNB GmbH 2016). As there is no reference to this new version on the English DGNB webpage (DGNB GmbH 2017), a previous version (2012) is used in this research.

Sustainability measures		Quality aspects
M1_timber	+	Architectural quality: warm character of timber products
	-	Indoor comfort: lower acoustical performance of timber structure
	-	Fire prevention: lower fire resistance of timber products
M2_recycled materials	+	Architectural quality: esthetical quality of reclaimed cobblestones
	-	Lower driving comfort
	-	Local impacts: increased traffic noise
E1_non-insulated	=	No impact on qualities, since the buildings are heated to the same comfort level
E2_passive standard	=	No impact on qualities, since appropriate summer ventialtion in buildings is assumed
E3_oil boiler	=	No impact on qualities, since the buildings are heated to the same comfort level
E4_heat pump	=	No impact on qualities, since the buildings are heated to the same comfort level
E5_no PV	=	No impact on qualities, since the buildings are connected to the public electrical grid
W1_no rainwater tank	=	No impact on qualities, since the buildings are connected to the drinking water network
W2_combined sewer	-	Local impacts: increased flood risk, no groundwater recharge (no infiltration)
W3_permeable areas	=	Rainwater infiltration is also implemented in the reference variants (drainage ditches)
L1_urban land	=	No impact on qualities, since the end situation is identical to the reference variants
L2_arable land	=	No impact on qualities, since the end situation is identical to the reference variants
L3_park	+	Green infrastructure: provision of a recreational green area (park)
	+	Local impacts: positive impact on outdoor comfort, urban heat island and air quality
T1_urban area	+	Accessibility and centrality: good access to facilities and services
	+	Transport infrastructure: good public transport facilities
T2_rural area	+	Green infrastructure: green living environment
	-	Accessibility and centrality: high distances to facilities and services
	-	Transport infrastructure: bad public transport facilities
T3_bicycle path	+	Safety and security: traffic safety for cyclers
	+	Transport infrastructure: cycling network

+	Positive impact on qualities
=	No impact on qualities
-	Negative impact on qualities

Figure 9.1: Assessment of qualities resulting from the sustainability measures.

Based on the assessment, four situations can be distinguished. First, some sustainability measures (L3_park, T1_urban area and T3_bicycle path) have a positive impact on qualities. For example, the provision of a park (L3) improves the access to recreational green areas and has a positive impact on outdoor comfort, urban heat island and air quality in neighbourhoods. Second, the variant including a combined sewer (W2) has a negative impact on qualities as there is an increased flood risk, compared to a separate sewer with drainage ditches. Third, some strategies (M1_timber, M2_recycled materials and T2_urban area) have both a positive and negative impact. For example, the use of reclaimed cobblestones for the paved areas (M2) can be appreciated from an esthetical point of view but results in a lower driving comfort and increased traffic noise. Finally, some sustainability measures have a neutral quality impact as the qualities are identical to the reference situation.

9.3 Scores of sustainability measures

In each scoring tool, different assessment issues can be linked to the main impact drivers, i.e. material use, operational energy use, operational water use, primary land use and user transport. An overview of these assessment issues and the related weighting factors for BREEAM Communities, DZM Wijken and DGNB New Urban Districts is given in Figure 9.2, Figure 9.3 and Figure 9.4 respectively.

In the three scoring tools analysed, the assessment issues related to the main impact drivers represent about 50 to 60% of the maximum score (100%). The remaining assessment issues mainly focus on quality aspects (i.e. functional qualities, technical qualities, site qualities, socio-cultural qualities and process qualities).

The relative weight of the assessment issues however varies importantly depending on the scoring tool. In BREEAM Communities (Figure 9.2), the highest weight is attributed to issues related to user transport (17.4%), followed by primary land use (12.4%). Issues related to operational water use, material use and operational energy use have a lower contribution of 8.5%, 8.1% and 4.1% respectively.

In DZW Wijken (Figure 9.3), assessment issues related to primary land use and user transport have the highest weight, i.e. 19.6% and 14% respectively. Material use, operational energy use and operational water use each represent 10%.

Finally, the highest weight in DGNB (Figure 9.4) is attributed to assessment issues related to primary land use (11.3%) and user transport (11.1%), followed by operational water use (7.6%). Operational energy use and material use have a low weight not exceeding 5%. However, compared to BREEAM and DZM Wijken, most of these aspects are also included in the E-LCA and LCC criteria, which represent 5.4% and 6.8% of the total score respectively.

Assessment issues	Weighting (%)
Material use	**8.1**
RE 02 – Existing buildings and infrastructure	2.7
RE 05 – Low impact materials	2.7
RE 06 – Resource efficiency	2.7
Operational energy use	**4.1**
RE 01 – Energy strategy	4.1
Operational water use	**8.5**
SE 03 – Flood risk assessment	1.8
SE 13 – Flood risk management	1.8
RE 03 – Water strategy	2.7
LE 03 – Water pollution	1.1
LE 06 – Rainwater harvesting	1.1
Primary land use	**12.4**
SE 11 – Green infrastructure	1.8
LE 01 – Ecology strategy	3.2
LE 02 – Land use	2.1
LE 04 – Enhancement of ecological value	3.2
LE 05 – Landscape	2.1
User transport	**17.4**
SE 12 – Local parking	0.9
RE 07 – Transport carbon emissions	2.7
TM 01 – Transport assessment	3.2
TM 02 – Safe and appealing streets	3.2
TM 03 – Cycling network	2.1
TM 04 – Access to public transport	2.1
TM 05 – Cycling facilities	1.1
TM 06 – Public transport facilities	2.1
TOTAL	**50.5**

Figure 9.2: BREEAM Communities assessment issues related to the main impact drivers.

Assessment issues	Weighting (%)
Material use	**10.0**
MAT 01.01 – Reuse of structures in the collective space	1.7
MAT 01.02 – Reuse of existing buildings, building elements and materials	1.7
MAT 01.03 – Closed soil balance	1.1
MAT 02.01 – Environmental impact of building materials in the collective space	2.1
MAT 02.02 – Environmental impact of building materials in buildings	1.4
MAT 03.02 – Waste management	1.3
MAT 03.01 – Material management	0.7
Operational energy use	**10.0**
ENE B.01.01 – Reduction of net energy demand of the neighbourhood	3.0
ENE B.01.02 – Renewable energy efficient microgrid	1.5
ENE B.01.03 – Non-renewable primary final energy consumption of the neighbourhood	3.0
ENE B.02.01 – Preparations renewable energy	1.8
ENE B.02.02 – Preparations thermal network	0.8
Operational water use	**10.0**
WAT 01.01 – Flood risk	0.4
WAT 01.02 – Site assessment	0.6
WAT 02.01 – Water use	1.5
WAT 02.02 – Rain water management	3.0
WAT 02.03 – Waste water management	0.5
WAT 02.04 – Groundwater	0.5
WAT 03.01 – Management of water system	0.9
WAT 03.02 – Maintenance friendliness	0.6
WAT 04.01 – Climate robustness of water system	0.8
WAT 04.02 – Water robustness	1.2
Primary land use	**19.6**
FYS 01.01 – Location of the development	4.7
FYS 01.02 – Soil quality	0.9
GRN 01.01 – Natural values	7.0
GRN 02.01 – Benefits of greenery	3.5
GRN 03.01 – Preparation management and maintenance	2.9
GRN 03.02 – Adaptive capacity	0.6
User transport	**14.0**
MOB 01.01 – Proximity to daily destinations	3.5
MOB 02.01 – 'STOP' mobility principle	3.2
MOB 02.02 – Access to public transport	1.4
MOB 02.03 – Transport facilities	4.6
MOB 03.01 – Transport information for future inhabitants, workers and visitors	1.1
MOB 03.02 – Adaptive capacity	0.4
TOTAL	**63.6**

Figure 9.3: DZM Wijken assessment issues, related to the main impact drivers.

Assessment issues	Weighting (%)
E-LCA	**5.4**
ENV1.1 – Life Cycle Assessment	2.7
ENV2.2 – Total primary energy demand and proportion of renewable primary energy	2.7
LCC	**6.8**
ECO1.1 – Life Cycle Costing	6.8
Material use	**1.8**
ENV2.4 – Resource saving infrastructure	1.8
Operational energy use	**4.4**
ENV2.3 – Energy efficient building structure	1.8
TEC1.1 – Energy technique	2.6
Operational water use	**7.6**
ENV1.2 – Water and soil protection	1.8
ENV2.6 – Water cycle system	1.8
TEC1.3 – Rain water management	4.0
Primary land use	**11.3**
ENV1.4 – Biodiversity and integration	1.8
ENV2.1 – Land use	2.7
ECO2.2 – Space efficiency	6.8
User transport	**11.1**
SOC1.2 – Social and profit oriented infrastructure	1.8
TEC3.1 – Quality of traffic system	4.0
TEC3.2 – Quality of street infrastructure	1.3
TEC3.3 – Quality of public transport infrastructure	1.3
TEC3.4 – Quality of cycling infrastructure	1.3
TEC3.5 – Quality of pedestrian infrastructure	1.3
TOTAL	**48.3**

Figure 9.4: DGNB New Urban Districts assessment issues, related to E-LCA, LCC and the main impact drivers.

For each sustainability measure, the BREEAM, DZM Wijken and DGNB scores are calculated (Figure 9.5). The score calculation is reported in detail in Appendix D. The results are expressed as a score increase or reduction, compared to the score of the reference new neighbourhoods. To simplify the analysis only the assessment issues which are influenced by the analysed sustainability measures and variations in urban layout and built density have been considered. Furthermore, aspects and parameters which are undefined or unknown are not assessed. For example, the provision of cycle parking in the neighbourhood models is not defined and therefore not included in the analysis.

A number of observations can be reported from the score calculation. First, many criteria focus on process aspects, rather than achieved performance levels. For example, scores are awarded for criteria related to concept finding, planning, quality control and the involvement of experts. Even if these aspects can be a mean to achieve the sustainability goals, there is no guarantee for real sustainability performance improvements. Second, the assignment of scores is often based on discontinuous score scales. As a result, variations between the analysed measures do not automatically lead to variations in score. Third, many criteria stimulate measures which go further than the current building standards. A typical example are the criteria related to the energy performance. The scoring tools do not allow to analyse the influence of lower performance levels nor to assess the sustainability of renovation measures in existing neighbourhoods (any lower performance level, whatever this level is, results in a zero score for the energy performance criteria). Finally, the consequences of burden shifting between sustainability aspects are not taken into account in scoring tools[3]. For example, credits are awarded for improvements in energy efficiency, without considering the potential impact increase related to material use.

Next to these global observations, three specific remarks can be formulated for the DGNB scoring tool. First, the translation of the E-LCA and LCC results to scores and the weighing with other quantitative and qualitative criteria lead to a loss of information and make the life cycle impact results not directly visible in the total score. Furthermore, the influence of the E-LCA and LCC criteria on the total score is limited due to the relatively low weighting (about 12% of the total score). This low weighting is also not proportional to the time effort which is required for the life cycle impact calculations. Second, there are some inconsistencies in the score assignment. For example, the score for the LCC results (ECO1.1- Life Cycle Costing) is for 60% based on the financial impact of the infrastructure and open spaces and for 40% on the impact of the buildings. This is not in line with the contribution of the external elements to the life cycle financial impact of neighbourhoods, which varies from about 5 to 30% depending on the analysed neighbourhood model. Third, material use, operational energy use, operational water use and user transport are not only assessed in the E-LCA and/or LCC criteria but also in specific assessment issues (Figure 9.4). This leads to a kind of double counting, which is questionable.

	Detached			Semi-detached			Terraced			Apartment		
	BREEAM	DZM	DGNB	BREEAM	DZM	DGNB	BREEAM	DZM	DGNB	BREEAM	DZM	DGNB
Reference_new	6.6	8.8	17.1	6.6	9.2	17.7	6.9	9.2	18.7	5.8	7.5	19.4
M1_timber	0.0	0.0	-0.1	0.0	0.0	-0.0	0.0	0.0	-0.1	0.0	0.0	+0.0
M2_recycled materials	+1.4	+2.1	-2.3	+1.4	+2.1	-2.4	+1.4	+2.1	-2.2	+1.4	+2.1	-2.9
E1_non-insulated	-0.7	0.0	-2.2	-0.7	-0.4	-2.1	-1.1	-1.6	-2.1	-0.4	-0.1	-1.1
E2_passive standard	+1.5	+3.0	+0.8	+1.5	+2.6	+0.7	+1.1	+1.4	+0.6	+1.1	+2.9	+0.5
E3_oil boiler	-0.7	0.0	-1.2	-0.7	-0.4	-1.2	-1.1	-1.6	-1.3	-0.4	-0.1	-1.0
E4_heat pump	+1.1	+0.3	-0.5	+1.1	+0.6	-0.5	+0.7	+0.3	-0.5	+0.7	+0.0	-0.6
E5_no PV	-0.7	0.0	-0.4	-0.7	-0.4	-0.6	-1.1	-1.6	-0.6	-0.4	-0.1	-0.2
W1_no rainwater tank	-1.1	-0.4	-0.6	-1.1	-0.4	-0.6	-1.1	-0.4	-0.6	-0.7	0.0	-0.4
W2_combined sewer	-1.8	-1.9	-0.9	-1.8	-1.9	-0.9	-1.8	-1.9	-0.9	-1.8	-1.9	-0.9
W3_permeable areas	0.0	+0.5	-0.0	0.0	0.0	-0.0	0.0	0.0	-0.1	0.0	0.0	-0.1
L1_urban land	+0.7	+4.4	0.0	+0.7	+4.4	0.0	+0.7	+4.4	0.0	+0.7	+4.4	0.0
L2_arable land	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
L3_park	+2.9	+1.0	+0.9	+2.9	+0.5	+1.1	+2.9	+1.9	+1.5	+2.9	+1.9	+2.2
T1_urban area	+0.5	+0.9	+2.9	+0.5	+0.9	+3.0	+0.5	+0.9	+3.0	+0.5	+0.9	+3.0
T2_rural area	-1.1	-1.0	-0.9	-1.1	-1.0	-0.9	-1.1	-1.0	-0.9	-1.1	-1.0	-0.9
T3_bicycle path	+2.1	+0.9	+0.3	+2.1	+0.6	+0.2	+2.1	+0.9	+0.6	+2.1	+0.9	+0.9

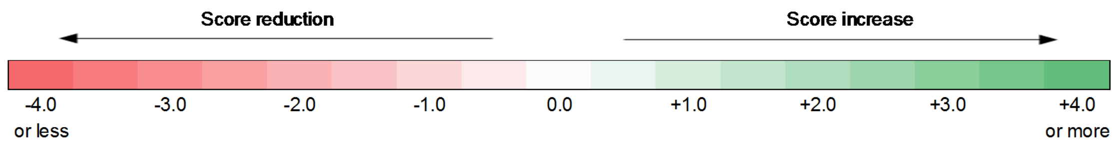

Figure 9.5: BREEAM, DZM Wijken and DGNB scores of the sustainability measures analysed. The first row includes the percentage points obtained for the reference new variants considering the limited set of assessment issues. The following rows include the increase or reduction of the percentage points (indicated with a red to green colour scale) when the sustainability measure is applied.

[3] In DGNB the impact of burden shifting is considered in the E-LCA and LCC criteria.

When analysing the scores of the various sustainability measures (Figure 9.5), the colour scale reveals important variations between the scoring tools. In BREEAM Communities the highest increases in score compared to the reference new neighbourhoods are obtained for the park and bicycle path variants (L3 and T3). Other significant increases of more than 1 percentage point are obtained for the following measures: M2_recycled materials, E2_passive standard and E4_heat pump. On the other hand, the highest score reductions are noticed for the variants with a combined sewer (W2), followed by the variants located in a rural area (T2) and without rainwater tank (W1).

In DZM Wijken three strategies result in a high increase in score in all neighbourhood models: L1_urban land, E2_passive standard and M2_recycled materials. Significant increases are also noticed for the park variant (L3) for the terraced house and apartment model[4]. Score reductions of more than 1 percentage point are obtained in all models for the variant with a combined sewer (W2). In contrary to the detached house, semi-detached house and apartment models, the terraced house model shows significant score reductions for the following energy related measures: E1_non-insulated, E3_oil boiler and E5_no PV[5].

In DGNB New Urban Districts the highest increases in score increases are noticed for the location in a urban area (T1) and the provision of a park (L3). Score reductions of more than 1 percentage point are obtained for the following strategies: M2_recycled materials, E1_non-insulated and E3_oil boiler. Compared to BREEAM Communities and DZM Wijken, an opposite picture is obtained for the following measures: M2_recycled materials and E4_heat pump. While these measures result in an increase of the score in BREEAM and DZM wijken, a score reduction is obtained in DGNB[6].

9.4 Comparison of life cycle impacts, qualities and scores

For an insightful comparison of our integrated life cycle approach with the scoring tools, the results of both assessments are displayed on charts with two vertical axes showing respectively the E-LCA, LCC or quality results (left vertical axis) versus the BREEAM, DZM Wijken and DGNB scores (right vertical axis). In these charts, reductions in life cycle financial or environmental cost are oriented in the same direction as an increase in score. The charts for the detached house model are shown in Figure 9.6, Figure 9.7 and Figure 9.8. The charts for the other neighbourhood models are reported in Appendix E, as similar trends are found.

[4] The scores are higher for the terraced house and apartment model as the provision of a park has a higher influence on the Urban Heat Island index of these models (assessment issue "FYS 02.01 – Urban heat island").

[5] This is a consequence of the higher energy related score for the reference variant of the terraced house model, which leads to higher score reductions when lower energy standards are applied.

[6] For the variant with recycled materials, the score reduction in DGNB is due to the high financial cost of cobblestones which is considered in the assessment issue "ECO1.1 – Life Cycle Costing". For the variant with heat pump, the score reduction in DGNB is due to the high primary energy factor of the fuel for heating (electricity), which is considered in the assessment issue "TEC1.1 – Energy technique".

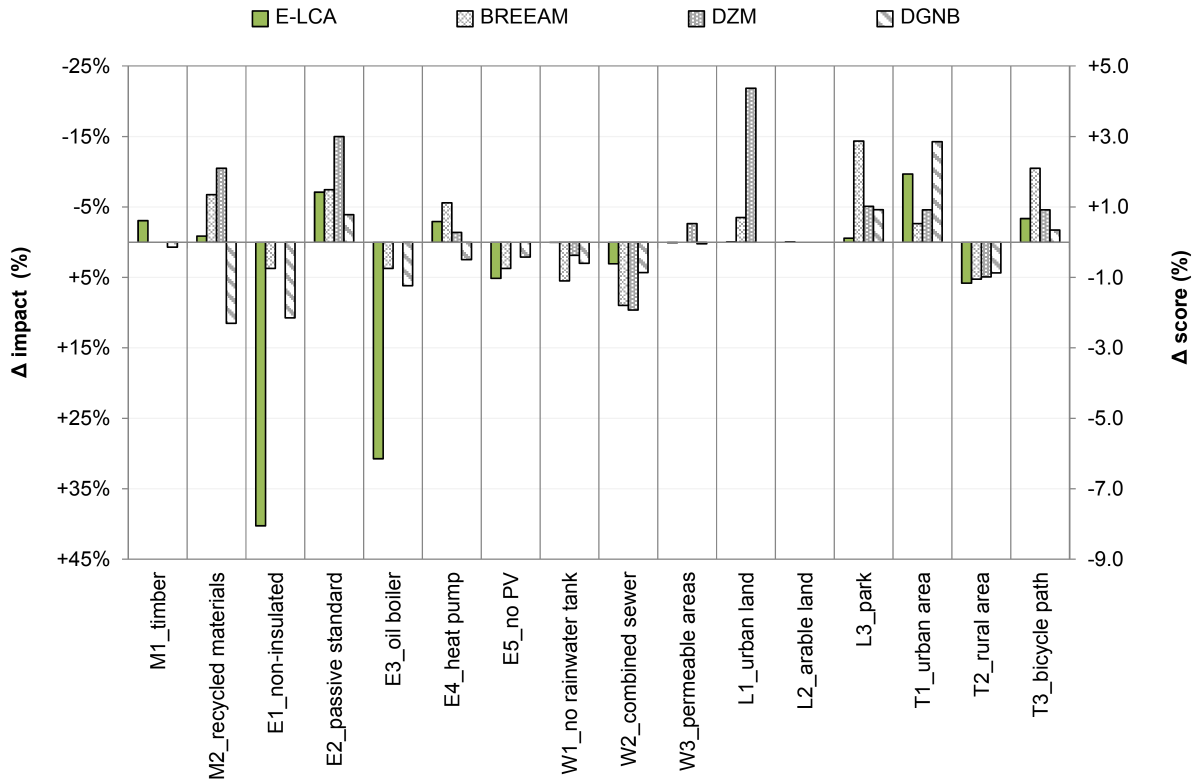

Figure 9.6: Comparison of the E-LCA results for the sustainability measures with the BREEAM, DZM Wijken and DGNB scores (Model 1_detached). The E-LCA impact and score variations compared to the reference new neighbourhood are shown on the left and right vertical axis respectively.

In a first step, the scores are compared with the E-LCA results (Figure 9.6). The comparison shows that none of the scoring tools has a good overall fit with the life cycle impact results for the measures analysed. While the highest variations in E-LCA results are obtained for the sustainability measures related to operational energy use (E1 and E3) and user transport (T1), relatively high score variations are found for measures spread over the various drivers.

For the material related sustainability measures, an opposite picture is noticed between the E-LCA results and the scores. Based on the E-LCA, higher life cycle impact reductions are obtained for the use of timber in buildings (M1), compared to the use of recycled materials for the paved areas (M2). In the scoring tools, the score variations are relatively high for measure M2 and negligible for measure M1. The reason is that material related criteria in scoring tools for neighbourhoods especially focus on the material choice in the public space rather than the material choice in buildings.

Concerning the energy related sustainability measures, the variations in life cycle environmental impact are much higher than the variations in scores. The scoring tools do not reflect the high environmental impact increases for the non-insulated (E1) and oil boiler variants (E3). For these sustainability measures, substantial score reductions are only obtained in DGNB, as a result of the integration of E-LCA criteria. Regarding the passive variant (E2), the heat pump variant (E4) and the variant without PV panels (E5), a relatively good fit is found for the BREEAM results. In DZM Wijken the very high score for the passive variant is not in line with the impact reduction. In DGNB the score reduction for the heat pump variant is in contradiction with the improvement of the life cycle environmental impact.

For the strategies related to water use, a similar picture is obtained for the variant with permeable paved areas (W3), as the variations in score and E-LCA impact are both negligible. However, the score reductions for the variant without rainwater tank (W3) and the variant with a combined sewer (W2) are quite high compared to the environmental impact variations.

Concerning the strategies related to primary land use, the variations in environmental impact are negligible[7]. However, high score increases are obtained for the urban land variant (L1) in DZM Wijken and for the park variant (L3) in all scoring tools.

When analysing the results for user transport, a relatively good fit is noticed between the DGNB scores and the E-LCA results, due the integration of E-LCA criteria in the DGNB tool. In BREEAM and DZM Wijken the limited score increase for the variant located in a urban area (T1) is not consistent with the high reduction in life cycle environmental impact. Furthermore, a high score increase is awarded for the bicycle path variant (T3) in BREEAM, which is not in line with the limited reduction in environmental impact.

In a second step, the scores are compared with the LCC results (Figure 9.7). Only the DGNB scores are considered as the assessment of the economic dimension in BREEAM Communities and DZM Wijken focuses on the impact on local economy and job creation and not on the cost effectiveness of the implemented measures. A comparison between the BREEAM, DZM scores and LCC results is therefore irrelevant.

As for the E-LCA results, many discrepancies are found between the DGNB scores and the life cycle financial impact results for the measures considered. Concerning the material related sustainability measures, the timber frame variant (M1) leads to a high increase in financial cost but has a negligible impact on the DGNB score. On the other hand, the use of recycled materials for paved areas (M2) has a low influence on the financial cost but a high impact on the DGNB score. The reason is that DGNB assigns a higher weight to the LCC criteria for the infrastructure and open spaces, compared to the LCC criteria for the buildings.

When considering the energy related sustainability measures, a relatively good fit is found for the majority of the sustainability measures, except for the passive variant (E2). In that case, the relatively high DGNB score is not in line with the negligible reduction of the financial impact.

For the measures related to operational water use, the variations in financial cost are negligible but significant score reductions are noticed for the variant without rainwater tank (W1) and with a combined sewer (W2).

[7] Higher variations in environmental cost are obtained for the urban land (L1) and arable land variant (L2), based on the alternative monetisation scenario MMG_PDF (see Chapter 8).

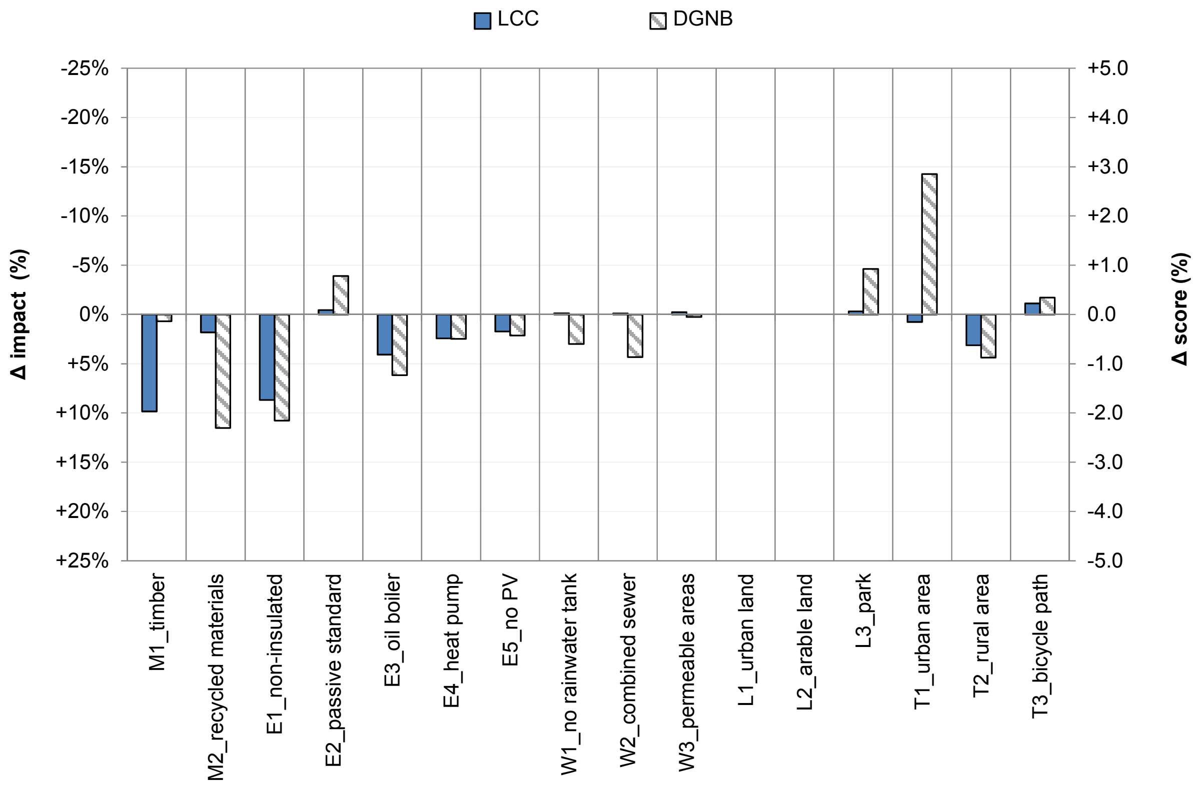

Figure 9.7: Comparison of the LCC results for the sustainability measures with the DGNB scores (Model 1_detached). The LCC impact and score variations compared to the reference new neighbourhood are shown on the left and right vertical axis respectively.

For the strategies related to primary land use, the high score increase obtained for the park variant (L3) is not in line with the negligible variation in financial cost.

Regarding the user transport related sustainability measures, a good fit is found between the DGNB scores and the LCC results for the variant located in a rural area (T2) and with bicycle paths (T3). However an opposite picture is obtained for the location in an urban area (T1) with a small increase in financial cost and a high increase in DGNB score. The reason is that the financial cost of building land, which is higher in an urban area, is not included in the LCC calculations in DGNB.

In a last step the scores are compared with the results of the quality assessment (Figure 9.8). To enable a comparison with the scoring tools, a quality score of + 2 and -2 is assigned to the sustainability measures with respectively a positive and negative impact on qualities. No quality score is awarded for measures which have both a positive and negative impact on qualities or are considered as neutral. For the comparison only the results for the sustainability measures with an impact on qualities are displayed in the chart (Figure 9.8).

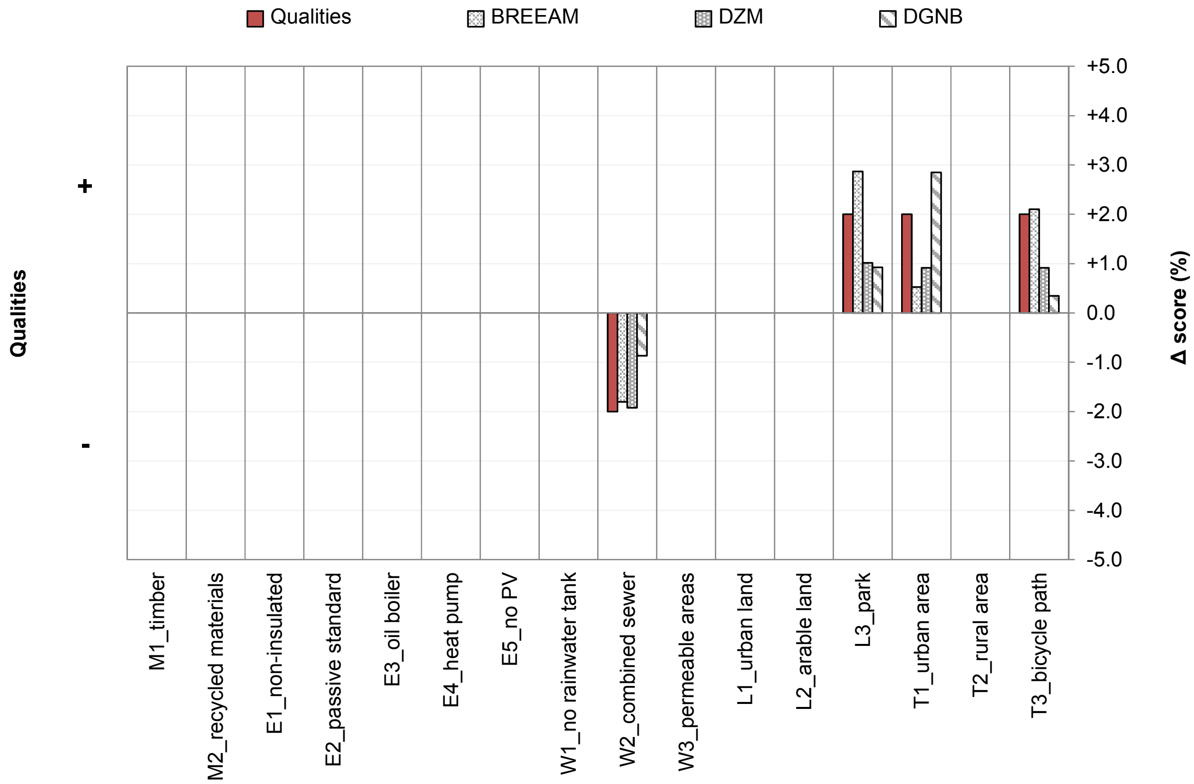

Figure 9.8: Comparison of the qualities resulting from the sustainability measures[8] with the BREEAM, DZM Wijken and DGNB scores (Model 1_detached). The results are expressed as a variation in quality (left vertical axis) or score (right vertical axis) compared to the reference new neighbourhood.

Compared to the E-LCA and LCC results, a greater level of similarity is seen between the quality assessment and the scores in BREEAM, DZM Wijken and DGNB. Measures with a positive impact on qualities (L3_park, T1_urban area and T3_bicycle path) result mostly in a relatively high score increase. On the other hand the variant with a combined sewer (W2) leads to relatively high score reductions which are in line with the negative impact on qualities.

However, large differences are found between the scoring tools. In BREEAM a higher score increase is obtained for the park and bicycle path variant (L3 and T3), while DGNB assigns a much higher score to the location in an urban area (T1), compared to the other scoring tools. The same applies to the variant with a combined sewer, where the score reduction is much lower in DGNB.

[8] Only the results for the sustainability measures with an impact on qualities are displayed in the chart.

9.5 Impact of urban layout and built density

In this section the influence of the urban layout and built density on the life cycle impact results and sustainability scores is compared. For this purpose, the results for the measures applied to the four neighbourhood models are displayed in charts, showing the life cycle impact or score (vertical axis) in function of the investment cost (initial financial cost) (horizontal axis) (Figure 9.9 to Figure 9.13)[9].

As already discussed in Chapter 8, the influence of the urban layout and built density is clearly noticeable for the E-LCA and LCC results (Figure 9.9 and Figure 9.10). Depending on the analysed sustainability measure, the life cycle environmental and financial cost of the model consisting of apartments is respectively 10 to 30% and 20 to 30% lower compared to the detached house model.

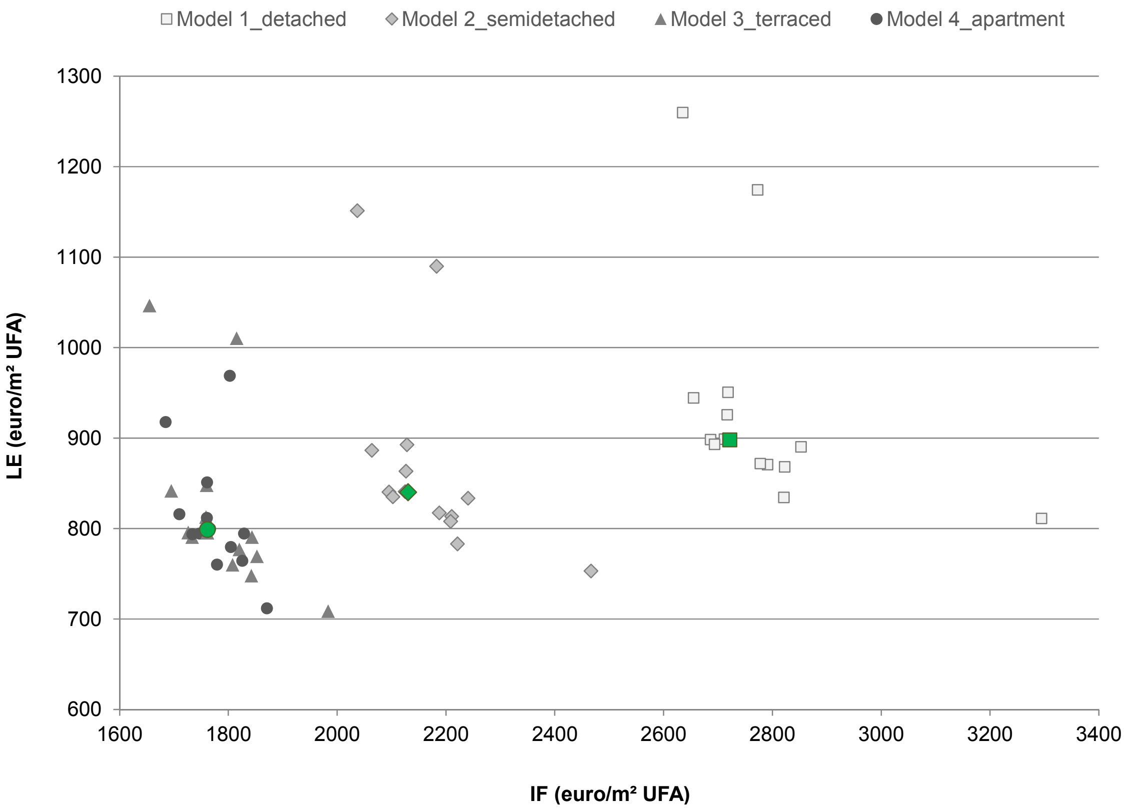

Figure 9.9: Life cycle environmental (LE) versus initial financial cost (IF) of the sustainability measures, applied to the four neighbourhood models. The reference new neighbourhoods are indicated in green.

[9] To improve the visualisation of the results and avoid an illegible concentration of data points, the x- and y-axis of the charts do not start at 0.

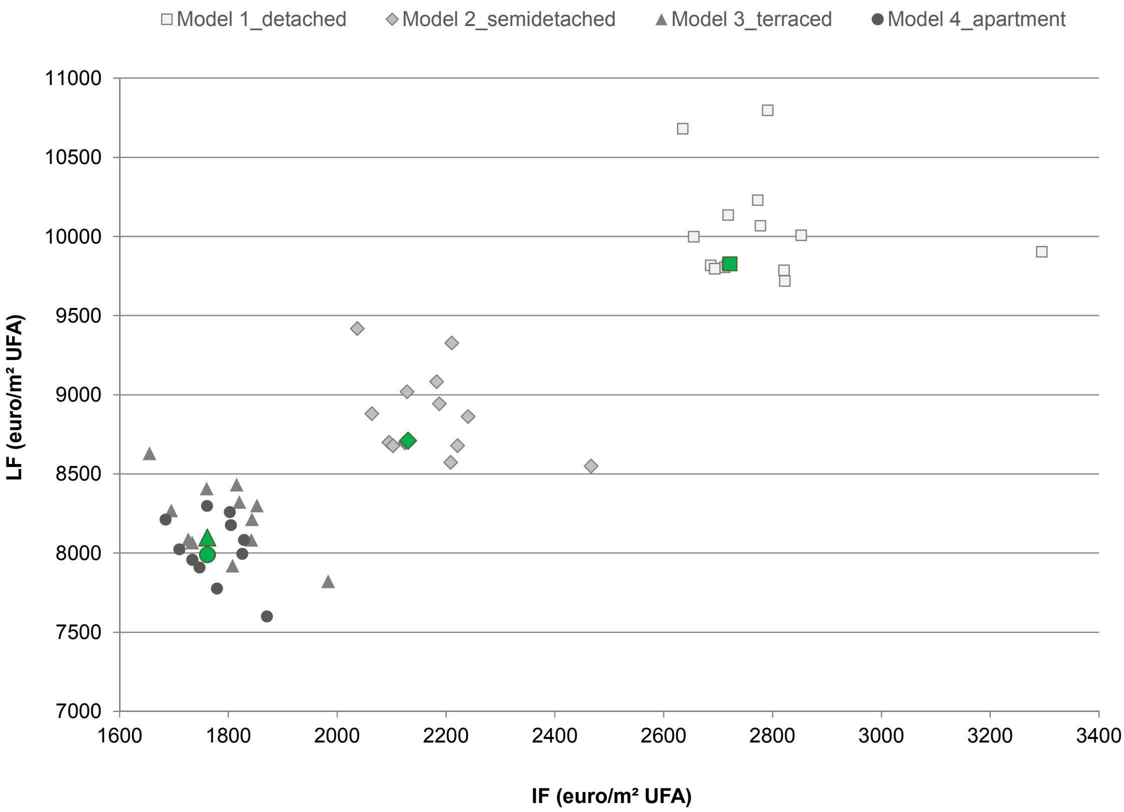

Figure 9.10: Life cycle financial (LF) versus initial financial cost (IF) of the sustainability measures, applied to the four neighbourhood models. The reference new neighbourhoods are indicated in green.

In BREEAM Communities and DZM Wijken (Figure 9.11 and Figure 9.12)[10], the total scores[11] per sustainability measure are quite similar between the models consisting of single-family houses with no preference for models with a higher built density. Furthermore the total scores for the apartment model are about 0.5 to 1.5 percentage points lower (depending on the analysed sustainability measure) than those for the single-family houses, which is in contradiction with the E-LCA and LCC results. The reasons are the lower potential for PV production and rainwater reuse but also the higher Urban Heat Island index in the apartment model which have a negative influence on the scores.

Compared to the other scoring tools, the positive influence of the urban layout and built density is clearly noticeable in the DGNB scores (Figure 9.13)[10]. The total scores for the apartment model are about 2.5 percentage points higher than for the detached house model. The reason is the integration in DGNB of a specific assessment issue focussing on the built density ("ECO 2.2 – Space efficiency").

[10] To improve the comparability with the E-LCA and LCC results, the y-axis is plotted in reversed direction as an increase in score should correspond with a reduction in environmental and/or financial impact.

[11] As mentioned in section 9.3, the total scores are calculated based on the assessment issues which are influenced by the analysed sustainability measures and/or variations in urban layout and built density.

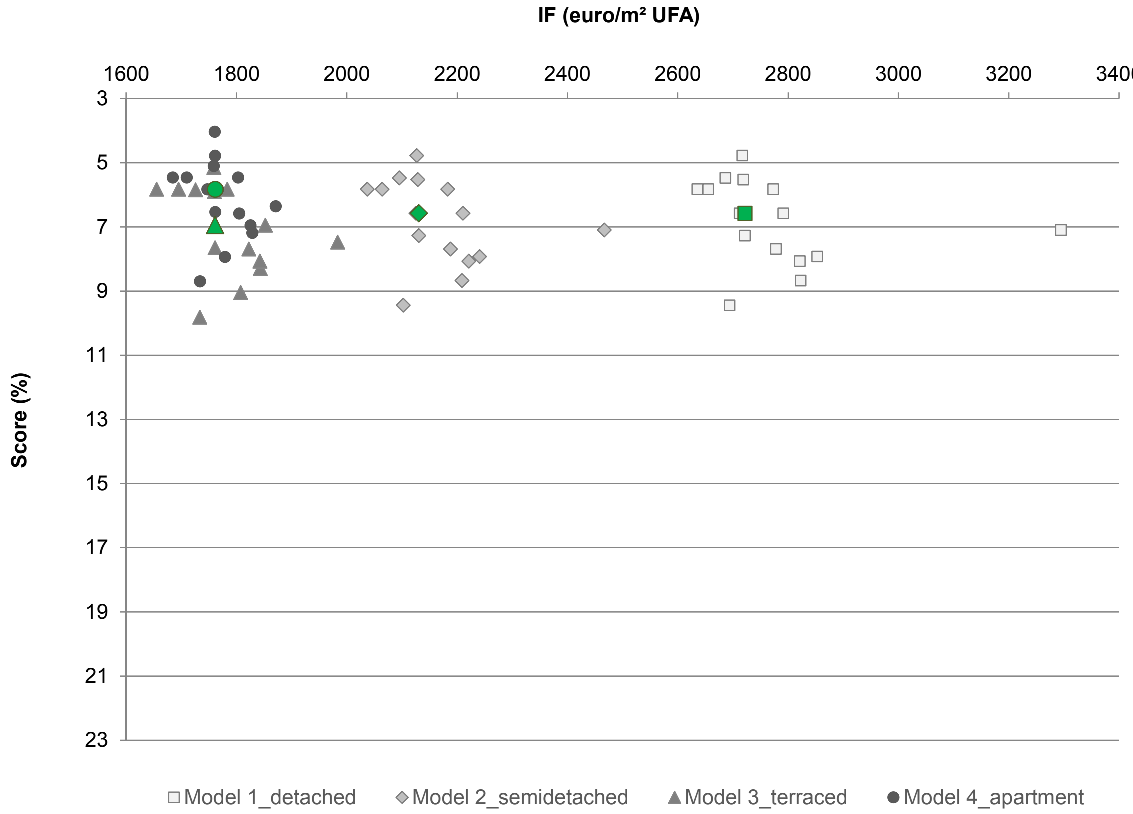

Figure 9.11: BREEAM scores versus initial financial cost (IF) of the sustainability measures, applied to the four neighbourhood models. The reference new neighbourhoods are indicated in green.

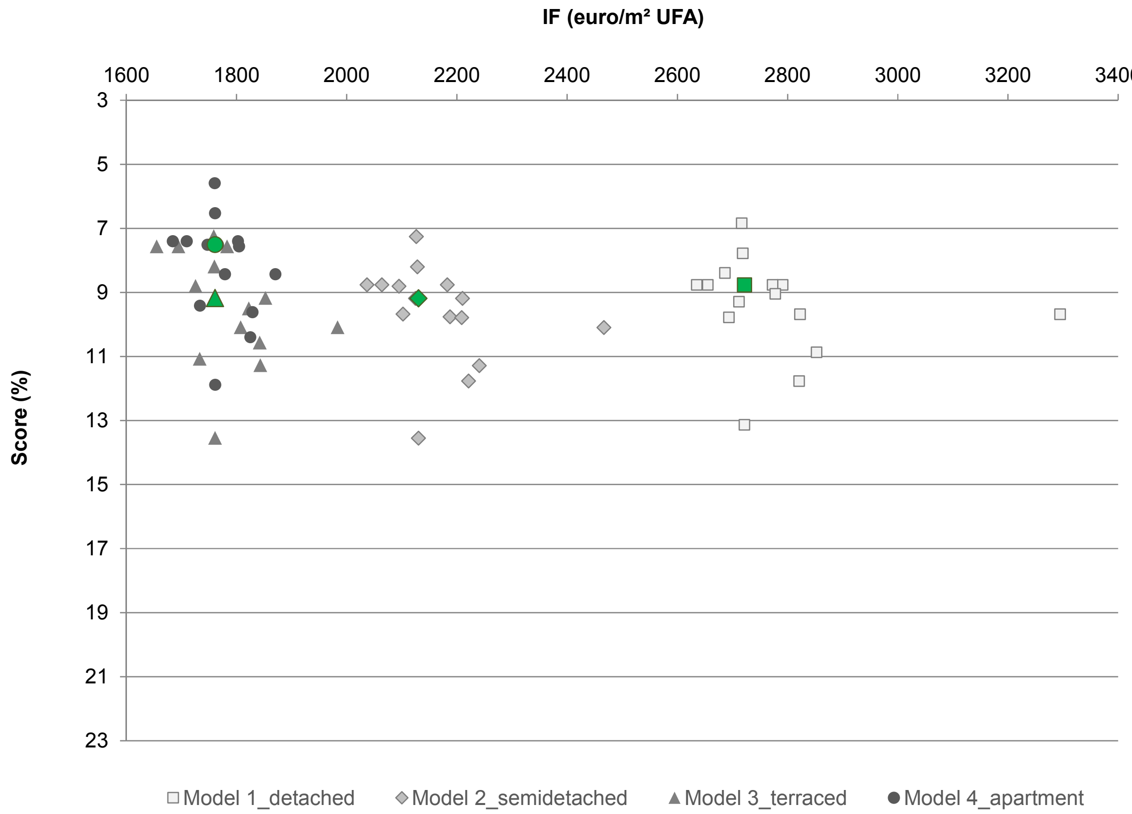

Figure 9.12: DZM Wijken scores versus initial financial cost (IF) of the sustainability measures, applied to the four neighbourhood models. The reference new neighbourhoods are indicated in green.

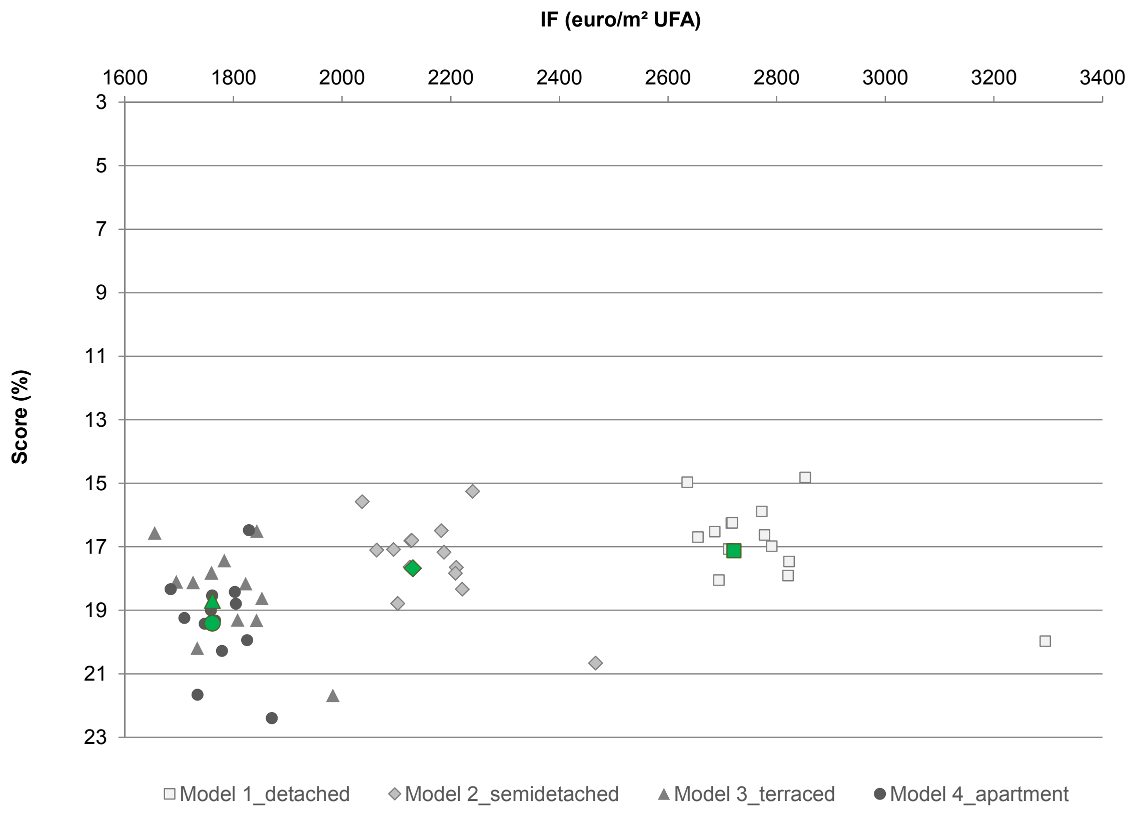

Figure 9.13: DGNB scores versus initial financial cost (IF) of the sustainability measures, applied to the four neighbourhood models. The reference new variants are indicated in green.

9.6 Conclusions and recommendations

In this chapter, the developed integrated life cycle approach, combining LCC, E-LCA and quality assessment, is compared with the scoring tools BREEAM Communities, DZM Wijken and DGNB New Urban Districts. Based on this analysis, two main conclusions can be formulated. First, despite some convergences, many discrepancies are found between the awarded scores and the E-LCA and LCC results. The score variations for the analysed sustainability measures are often not in line with the life cycle impact variations. A greater level of similarities was found for the quality assessment, as scoring tools integrate many quality criteria in their assessment issues. Second, the high influence of the urban layout and built density on the life cycle financial and environmental impact of neighbourhoods is not reflected in the awarded BREEAM and DZM scores. Score increases for higher built densities are only obtained in DGNB, which includes a specific assessment issue focussing on the built density.

From the comparative analysis, we can hence conclude that despite the broad application of the scoring tools, these are not a guarantee for a reduction of the life cycle financial and environmental impacts of neighbourhoods[12]. If we aim for truly sustainable neighbourhoods,

[12] Due to the large number of assumptions and uncertainties which are related to the E-LCA and LCC results, we recommend to validate this conclusion based on a sensitivity analysis (see recommendations for further research in Chapter 10)

we are convinced that evaluating the life cycle environmental impacts is crucial and that linking these with life cycle costs will also ensure affordability and cost effectiveness. Both life cycle environmental and financial costs are however not well covered in the currently available sustainability scoring tools.

Three recommendations are formulated to improve the scoring tools analysed in order to better capture environmental and financial issues. Firstly, the weighting factors in scoring tools should be adjusted based on a detailed life cycle study of the assessment issues. Secondly, a clear distinction is recommended between performance and process related criteria as the latter are a mean to achieve sustainability goals but do not necessarily guarantee real sustainability improvements. Thirdly, it is recommended to integrate life cycle evaluation criteria in scoring tools as done in DGNB New Urban Districts. Although DGNB is seen as one of the most advanced tools, there are still some issues identified based on the comparative analysis. First, the translation of the E-LCA and LCC results to scores is not always consistent and leads to a loss of information. It is therefore recommended to report the life cycle impact results separately as they are very useful to support decision taking. Second, the weight of the E-LCA and LCC criteria is limited and should be increased to have a substantial influence on the total DGNB score. Third, aspects which are already included in the E-LCA and LCC analysis should not be assessed in other assessment issues to avoid double counting.

As these recommendations require a thorough adaptation of scoring tools, a better alternative could be to start from a life cycle approach and to refine the methodology in order to integrate aspects, which are not covered by E-LCA and LCC, such as the assessment of the social performance and qualities. The assessment method developed in this research provides a framework for such integrated approach, which can be further extended in future.

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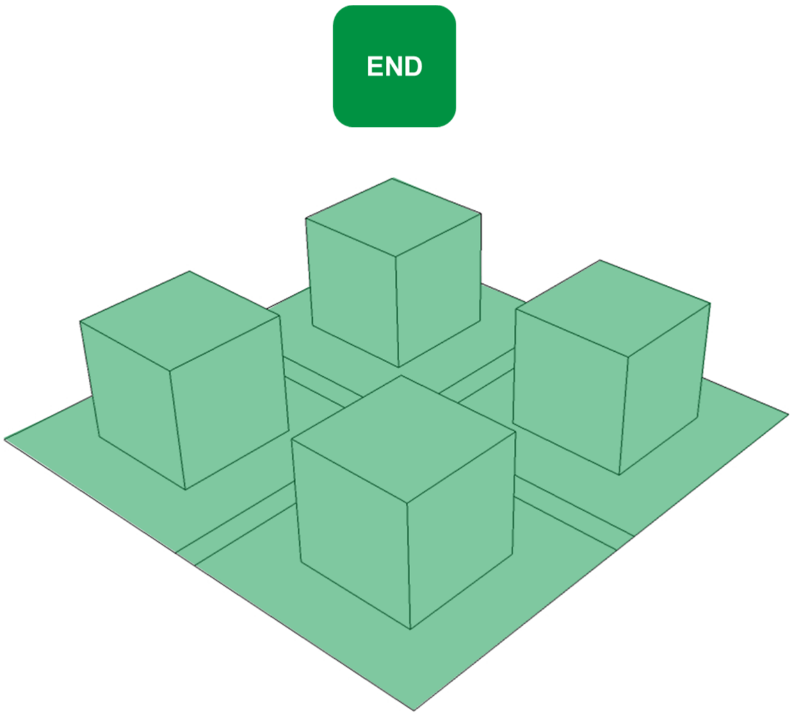
CHAPTER 10

Conclusions



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10.1 Main results and conclusions

In this PhD research a sustainability assessment method for neighbourhoods is developed using an integrated life cycle approach. This integrated life cycle approach combines an assessment of the economic, environmental and social performance of neighbourhoods, together with an assessment of the neighbourhood qualities. The method is used to assess the impact of neighbourhood networks (road infrastructure and utilities), open spaces (squares, parks and gardens) and a number of schematic neighbourhood models with various built densities. The method is furthermore compared with a number of well-known scoring tools for neighbourhoods in order to analyse their effectiveness in in improving the life cycle impacts and neighbourhood qualities. The main results and conclusions related to the assessment method, its application and the comparison with the scoring tools are summarised in the subsequent sections.

10.1.1 Elaboration of the assessment method

Integrated life cycle approach

The sustainability assessment method for neighbourhoods is based on an existing assessment method for buildings developed in the SuFiQuaD research project (Allacker 2010; Allacker et al. 2013a). The SuFiQuaD method combines an assessment of the economic and environmental performance of buildings, based on respectively LCC and E-LCA, with an assessment of the building qualities based on a Multi-Criteria Analysis (MCA).

Compared to the original SuFiQuaD method three main methodological refinements are developed. First, the method is updated to be in line with the current European standards related to the sustainability of construction works (CEN 2010; CEN 2011; CEN 2015). The system boundaries and life cycle modules defined in these standards are followed, which increases the transparency and comparability of the results with other LCC and E-LCA studies. The most recent version of the MMG E-LCA method (Allacker et al. 2013b; De Nocker and Debacker 2015) is used for the environmental impact assessment, which is based on the most recent E-LCA standards and guidelines in Europe (CEN 2011; EC-JRC 2011; CEN 2013).

Second, an assessment of the social performance is added in order to cover the widely accepted three dimensions (i.e. economic, environmental and social) of sustainability. As social life cycle assessment methods (S-LCA) are still under development (Sala et al. 2015), the social performance in this PhD research is evaluated as a part of the quality assessment (socio-cultural qualities) using an MCA.

Third, the modelling of the life cycle scenarios has been thoroughly refined to improve the calculation of periodic interventions and allow for future extensions such as the assessment of refurbishment activities.

Neighbourhood scale level

The life cycle methodology is extended from the building to the neighbourhood scale level, based on the principles of the element method for cost control. A distinction is made between various scale levels (i.e. building materials, work sections, building elements, buildings and neighbourhoods), where the results from the lower scale levels can be used for assessing the higher scale levels. To model constructions outside buildings such as road infrastructure, open spaces and utilities, the concept of external elements is elaborated.

This well-structured approach allows to deal with the complexity of the neighbourhood system and with the huge amount of data required in LCC and E-LCA. The approach is useable during the different design stages[1], from rough estimations based on predefined building elements in the master planning stage to detailed impact calculations in later design stages.

Extended evaluation scope

Compared to the original SuFiQuaD method, the evaluation scope is extended to include aspects which are influenced by decisions taken at the neighbourhood scale level. Five aspects are elaborated in detail. First, an adapted assessment of operational energy use is proposed which can be used during the master planning phase of neighbourhoods. This approach is based on the Equivalent Heating Degree Day (EHDD) method and includes an accurate calculation of the impact of solar gains. Second, the assessment of operational water use is refined, including a detailed calculation of the drinking water consumption and volumes of wastewater and rainwater discharge. Third, the impact of primary land use is assessed, considering the footprint of buildings, infrastructure and open spaces. Fourth, an approach is developed to assess the impact of user transport taking into account the characteristics of the built environment and provision of transport facilities. The latter is modelled in a simplified way to be appropriate for the master planning of neighbourhoods. Finally, a comprehensive framework is elaborated for the assessment of neighbourhood qualities.

A modular calculation model

The assessment method is implemented in a modular spreadsheet tool, which allows for both global impact assessments and detailed analyses of all impact contributors. The spreadsheet tool is tailored for the master planning phase as it enables rough estimations based on the use of predefined building element variants and default values for various parameters. The calculation model furthermore includes various graphical visualisations of the results to support interpretation.

[1] The applicability of the approach in the master planning stage was tested with students in the context of the design studio “Urban design” (3rd Bachelor Engineer-Architect – KU Leuven).

10.1.2 Application of the assessment method

The assessment method is applied both at the element and neighbourhood scale level by analysing the impact of external elements (networks and open spaces) and four schematic neighbourhood models, consisting of respectively detached houses, semi-detached houses, terraced houses and apartments.

Impact and contribution of external elements

The analysis highlighted that the contribution of the external elements (e.g. roads, gardens and squares) to the material impact of neighbourhoods is not negligible, especially in low built density neighbourhoods. For the model consisting of detached houses, the external elements contribute for about 20% to the life cycle environmental cost and for about 30% to the life cycle financial cost of material use. However this contribution is much lower for high built density neighbourhoods, i.e. about 10% and 5% respectively for the apartment model.

The analysis of the paved areas revealed the importance of the surface layer in the overall impact due to the required maintenance and replacements during the life cycle of the paved areas. The surface layer contributes for about 30-40% to the life cycle financial and environmental cost of the roads. Beside the paved areas, the utilities have a relatively high financial and environmental impact, which is of the same order of magnitude as the impact of the roads. This high impact is caused by the electric cables, which contribute to about 40-45% of the life cycle financial and environmental cost of utilities. Finally, the financial impact of green areas is highly dependent on the maintenance frequencies. A much higher life cycle financial cost is obtained for gardens compared to parks as the latter require less maintenance[2].

Influence of construction standards

The comparison between the reference variants representative for existing neighbourhoods (built before the 1970s energy crisis) and newly built neighbourhoods (year 2017) revealed the high influence of the construction standards. Compared to the existing variants, the life cycle environmental and financial cost of the new variants is about 60% and 30% lower respectively. The stricter energy performance requirements imposed by the EPB regulation (Flemish Government 2017a) clearly lead to an important reduction in the life cycle impact and cost of buildings. The regulation on rainwater management (Flemish Government 2016), including the provision of separated sewer, infiltration systems and rainwater reuse, was assessed as well. This analysis revealed that these requirements do not lead to a significant decrease in financial and environmental (global) impact. This relative low reduction is due to the low contribution of operational water use to the life cycle impacts and because the life cycle assessment method does not assess local effects (such as flood risk and the locally lowering of groundwater levels). The latter is however the main objective of this regulation.

[2] This conclusion is based on the assumption that all green areas are maintained by professional gardeners (self-build, cleaning and maintenance by the neighbourhood inhabitants is not considered in this research)

Influence of urban form and built density

The comparison between the neighbourhood models showed the high influence of the urban form and built density. The life cycle environmental cost of the model consisting of apartments is between 10%[3] and 45% lower compared to the detached house model for respectively the newly built and existing neighbourhoods. The trends are similar for the life cycle financial cost, with reductions of 20% and 30% respectively. Higher built densities and compactness lead to a lower energy use for heating and lower material use for buildings, network and open spaces. Furthermore, primary land use and the volume of rainwater discharge decrease importantly. Good urban planning is therefore essential to reduce the financial and environmental impact of neighbourhoods.

However, the impact reductions tend to flatten for high built densities. For the new neighbourhoods, the life cycle impacts of the apartment model are similar to the terraced house model. The reason is the lower potential for PV production in apartment buildings, the additional impact of collective circulation spaces and the high impact of pile foundations.

Main impact drivers and influencing parameters

Material use, operational energy use and user transport were identified as the main impact drivers, contributing together to more than 85% of the life cycle financial and environmental cost of neighbourhoods. Their relative contribution however varies between the financial and environmental cost as material use is the main contributor to the life cycle financial cost but a much lower contributor to the life cycle environmental cost. On the other hand, the contribution of primary land use and water does not exceed 10% in most cases.

Based on the analysis of various sustainability measures, four parameters were identified as having a high influence on the financial and environmental impact of neighbourhoods. First, high impact reductions are obtained for improved energy performance levels (including the insulation level, air-tightness and ventilation system), especially between the non-insulated and EPB 2017 variants. Second, an improved efficiency of the technical system for heating and domestic hot water leads to a substantial impact reduction, when comparing an 'old' non-condensing oil boiler with a condensing gas boiler. Third, the neighbourhood location has a major influence on user transport with high impact reductions between a rural and urban area. Finally, the material choice in buildings is an important parameter for the life cycle financial cost. Higher financial costs are found for the timber variants, compared to the solid variants.

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[3] The life cycle environmental cost reductions resulting from the increase in built density are limited for the newly built neighbourhoods. However, the indirect effects of the built density on the transport distances and efficiency of public transport are not considered in the assessment of the impact of user transport (see Chapter 8).

10.1.3 Comparison between the assessment method and scoring tools

The assessment method developed is compared with three well-known scoring tools for neighbourhoods: BREEAM Communities (BRE 2016), DZM Wijken (Flemish Government 2017b) and DGNB New Urban Districts (DGNB GmbH 2012). The comparison revealed many discrepancies between the life cycle impact results and the obtained scores for the analysed sustainability measures. Despite the large number of assumptions and uncertainties which are related to the LCC and E-LCA results, we can conclude that the use of scoring tools does not guarantee a reduction in life cycle financial and environmental impact of neighbourhoods.

A number of recommendations are formulated to better capture environmental and financial issues in scoring tools. This includes the adjustment of the weighting factors based on a detailed life cycle study, a clear distinction between performance and process related criteria and the integration of E-LCA and LCC criteria in scoring tools. The developed assessment method could also be used as a starting point to elaborate a refined methodology which assesses all dimensions of sustainability in a consistent way.

10.2 Overall reflection: a sustainability dilemma

During the Flemish climate summit on 19th April 2016 the following question was raised by the Flemish Government Architect Leo Van Broeck: "*Is a new-built passive detached house located in the countryside more sustainable than an existing terraced house located in a city centre?"*.

To answer this question, three case studies were compared with the assessment method developed in this PhD dissertation. In the first case study (Detached_rural_passive), the new-built neighbourhood model consisting of detached houses (defined in Chapter 8) is analysed considering an energy performance level in line with the passive standard and located in a rural area. In the second case study (Terraced_urban_non-insulated), the existing (non-insulated) variant of the terraced house model (defined in Chapter 8) is assessed for a location in an urban area. The third case study (Terraced_urban_lightly insulated) is similar to the second one but the energy efficiency of the terraced houses is improved by providing roof insulation (10 cm PIR), double glazed windows (instead of single glazed windows) and a condensing gas boiler (instead of an 'old' non-condensing oil boiler). The parameters of the three case studies are summarised in Table 10.1.

Table 10.1: Neighbourhood parameters of three case studies.

Parameter	Detached_rural_passive	Terraced_urban_non-insulated	Terraced_urban_lightly insulated
Material use			
Building elements	Solid structure	Solid structure	Solid structure
External elements	Surface layer in asphalt (roads and parking facilities) and concrete paving stones (footpaths and square)	Surface layer in concrete (roads, square and parking facilities) and concrete tiles (footpaths)	Surface layer in concrete (roads, square and parking facilities) and concrete tiles (footpaths)
Energy use			
Insulation level	Maximum U-values PHPP	No insulation and single glazed windows	Lightly insulated: roof insulation and double glazed windows
Air infiltration rate	1 $m^3/h.m^2$	12 $m^3/h.m^2$	12 $m^3/h.m^2$
Ventilation system	Mechanical supply and exhaust + heat recovery (system D+)	Natural ventilation (System A)	Natural ventilation (System A)
Heating system	Condensing gas boiler	Non-condensing oil boiler	Condensing gas boiler
Hot water production	Coupled instant boiler	Storage vessel, coupled to space heating	Coupled instant boiler
Renewable energy	Photovoltaic panels	-	-
Water use			
Rainwater collection	Rainwater tanks	-	-
Sewer type	Separate sewer	Combined sewer	Combined sewer
Infiltration system	Drainage ditches	-	-
Primary land use			
Original land use	Forest land	Forest land	Forest land
Neighbourhood land use	Urban discontinuously built	Urban discontinuously built	Urban discontinuously built
Building land price	Rotselaar (187.28 €/m^2)	Leuven (282.63 €/m^2)	Leuven (282.63 €/m^2)
User transport			
Reference transport profile	Rural area	Regional urban area - central municipalities	Regional urban area – central municipalities
Transport facilities	Average (no correction factor)	Average (no correction factor)	Average (no correction factor)

The results of the environmental impact assessment are shown in Figure 10.1. Compared to the passive detached house model, the life cycle environmental cost of the non-insulated terraced house model is about two times higher due to the high impact of operational energy use. However, a 4% lower life cycle environmental cost is obtained when the terraced house model is lightly insulated. In that case the higher impact of operational energy use and operational water use (compared to the passive variant) is fully compensated by the lower impact of material use and primary land use (resulting from the higher built density) and lower impact of user transport (resulting from the urban location).

Beside the environmental cost calculated based on all MMG impact indicators, an assessment is done based on the impact of global warming solely (Figure 10.1), as this environmental issue is currently the main focus in policy decision making. In that case, a slightly different picture is obtained as the environmental impact of the lightly insulated terraced house model is 8% higher, compared to the passive detached house model. Furthermore, the impact of operational water and primary land use is not reflected in the results for global warming as these drivers have only a high influence on other impact categories[4].

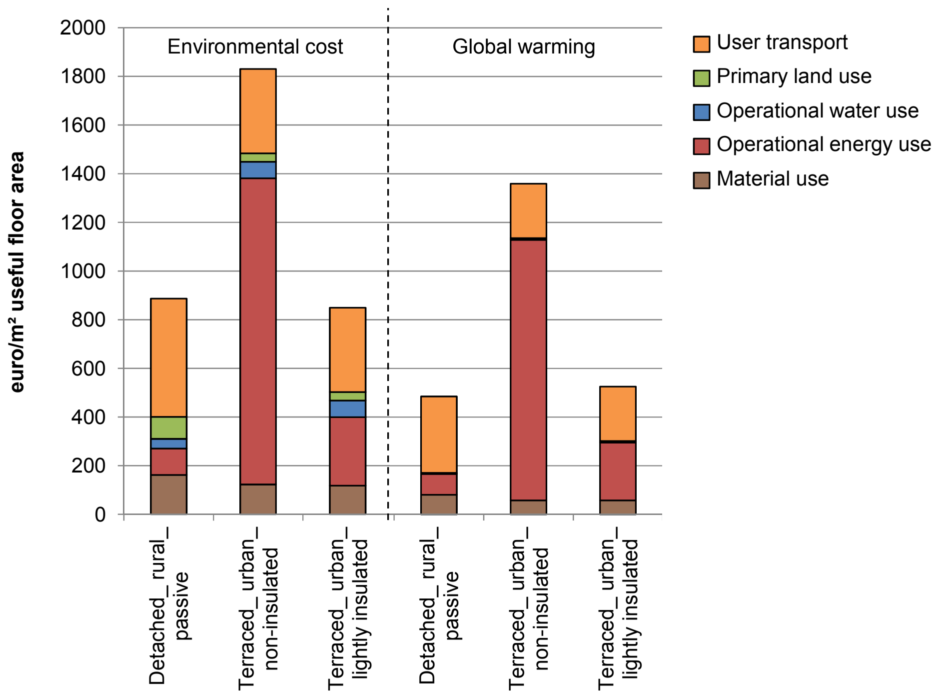

Figure 10.1: Life cycle environmental cost of the three case studies, subdivided per driver. Both the environmental cost calculated based on all MMG impact indicators (left) and based on the indicator global warming solely (right) are shown.

[4] Primary land use has only an influence on land use impact categories. Operational water use has only a high contribution to the following indicators: eutrophication, human toxicity (non-cancer effects) and water scarcity (see Chapter 8).

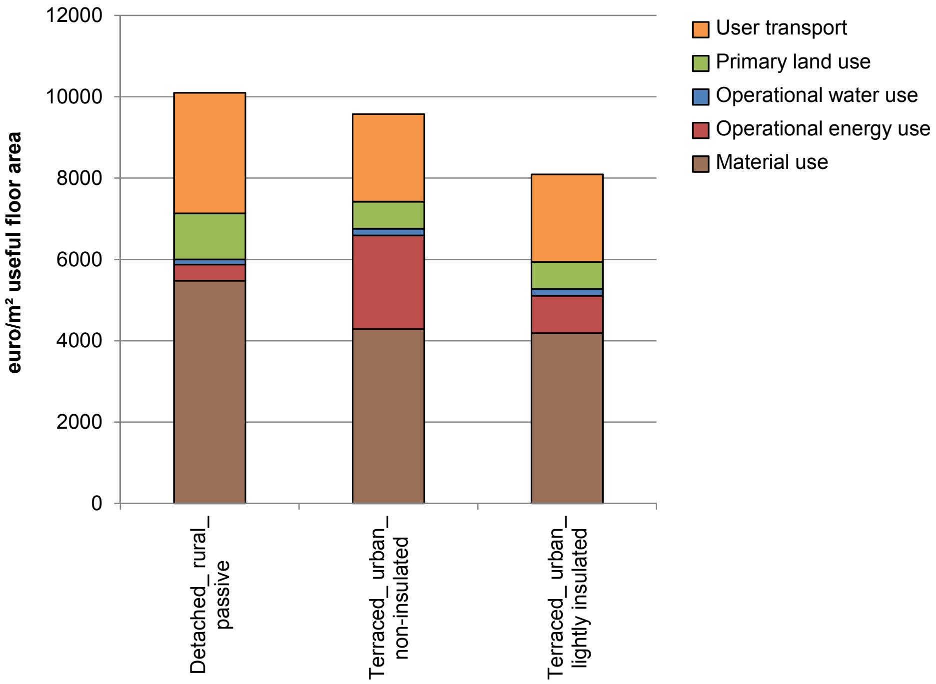

Figure 10.2: Life cycle financial cost of the three case studies, subdivided per driver.

When analysing the financial impact results (Figure 10.2), both the non-insulated and lightly insulated terraced house models have a lower life cycle cost compared to the passive detached house (reduction of 5% and 20% respectively). This again confirms the importance of the neighbourhood layout, built density and neighbourhood location.

Based on this analysis, we can conclude that an existing urban terraced house which is lightly insulated (roof insulation, double glazed windows and a condensing gas boiler) is more sustainable from a financial and environmental perspective than a detached passive house in the countryside. Furthermore, this analysis demonstrates that striving for sustainable neighbourhoods should not be limited to the optimisation of operational energy use. Other drivers such as material use, operational water use, primary land use and user transport should be considered as well. Finally, the optimisation should not only focus on global warming solely, but consider a wide range of impact categories such as included in the MMG E-LCA method.

10.3 Further research

A number of proposals are formulated for further research. These recommendations are related to the assessment methodology, application of the method, sensitivity analysis, model and data collection, extension to the higher scale levels and assessment of future scenarios.

Assessment methodology

It is recommended to further refine three aspects of the assessment methodology in future. First, further research should be done on the monetary valuation of environmental impacts as the uncertainties are still high (De Nocker and Debacker 2015). The high valuation of global warming compared to other impact categories, should be further investigated. Based on the current MMG method, global warming contributes to 70-75% of the life cycle environmental cost of the neighbourhoods models analysed and has therefore a major influence on the results. Furthermore, the valuation of land use impacts should be refined as biodiversity impacts related to land transformation are not valuated in the MMG monetisation method. A valuation of biodiversity impacts based on the loss of species (PDF), such as proposed in this research, could be an interesting approach. Finally, the contribution of the life cycle environmental cost to the life cycle total cost of neighbourhoods is relatively low (10-15%). As a result, decisions based on the total cost do not differ from decisions based on the financial cost solely. A much higher valuation of environmental impacts would be necessary to stimulate fundamental changes in the building sector. In this research, it was therefore chosen to report both the financial and environmental cost separately to highlight differences between the financial and environmental perspectives.

Second, the social performance is currently evaluated as a part of the quality assessment (i.e. socio-cultural qualities). Based on the future developments related to S-LCA, the assessment of the social performance should be included in the life cycle approach, together with the assessment of the economic (LCC) and environmental (E-LCA) performance.

Third, the assessment of the neighbourhood qualities was not the main focus of this research and was only developed conceptually. The global framework for the assessment of qualities should therefore be further elaborated. As in the SuFiQuaD method, quality scores and weighting could be defined for the various quality aspects, based on expert or stakeholder judgement. This refined framework should allow for a better integration of qualities in the assessment method and to search for a balance between the reduction of the neighbourhood impact and the maximisation of the total quality score.

Application of the method

In this PhD dissertation, the assessment method is applied to a limited number of neighbourhood models and selected element variants as the purpose was to illustrate the potential of the approach developed. A more extended analysis of neighbourhood layouts and technical solutions is required in order to formulate well-founded recommendations for the Belgian building stock. Such detailed study of the building stock was carried out at the building level in the SuFiQuaD research project (Allacker et al. 2013a) and could be done at the neighbourhood level based on the assessment method developed.

Furthermore, the scope of this research was limited to new-built residential neighbourhoods (even if the impact of older construction standards is evaluated). Further research should focus on the assessment of mixed use neighbourhoods and refurbishment projects, which would increase the applicability of the method.

Finally, the analysis of the services for space heating and domestic hot water in this research is limited to individual systems. The method should therefore be extended to assess collective systems such as district heating and inter-building energy exchanges, as an increasing importance of such systems is noticed in new neighbourhood developments.

Sensitivity analyses

The life cycle impact calculations are based on a huge number of input data, scenarios and assumptions. To improve the validity of the conclusions, detailed sensitivity analyses should be done considering the economic parameters, the uncertainties related to the environmental and financial data, the implemented life cycle scenarios and the calculation methods used. Furthermore, these analyses should allow to highlight the hotspots to focus on in future updates of the assessment method.

Model and data collection

The life cycle impact assessment of neighbourhoods requires a huge amount of input data. The use of Building Information Modelling (BIM) could help designers to collect information on the neighbourhood geometry and building elements. The use of a 3D neighbourhood model to extract input data for heating energy demand and E-LCA/ LCC calculations was investigated in a parallel study (Trigaux et al. 2017) and should be further elaborated. Furthermore, the link between BIM and dynamic energy simulations should be considered in order to include the impact of overheating and cooling and the availability of daylight in buildings.

Extension to the higher scale levels

The assessment method could be extended to assess the impact of cities. Following the principles of the bottom-up approach, additional scale levels could be added on top of the neighbourhood scale level. Impact results for various types of neighbourhoods could then be combined to calculate the impact of larger entities. The major advantage of such an approach compared to top-down approaches is the granularity of the data and hence the ability to identify the environmental hot spots. This is seen as an important added value to define strategies to move towards a more sustainable built environment.

Assessment of future scenarios

In this research, representative neighbourhoods in line with current Belgian building practice were assessed to test the methodology developed. In the overall ambition to move towards a more sustainable society, fundamental changes are expected which will affect the building sector importantly. Expected changes are amongst others the rise of a sharing economy, the evolution towards a more circular economy, a decarbonisation of energy production and a shift in more sustainable transport modes. Each of these will influence the overall impact of the built environment. The rise of a sharing economy for example will probably lead to new innovative building concepts such as co-housing, shared spaces and facilities. These new concepts could result in a more efficient use of space and built areas and reduce the amount of underused dwellings, which characterizes the current Flemish dwelling stock (de Weijer 2014). The evolution towards a more circular economy will hopefully lead to changes in processes related to the end-of-life of buildings and building components. A more dynamic design of buildings, using concepts like disassembly, adaptability and transformability, could stimulate the reuse and recycling of building elements and materials (Paduart et al. 2013; Trigaux et al. 2013). The decarbonisation of the energy production will include an increased share of renewable energy (European Commission 2017) while the Belgian electricity mix is currently dominated by nuclear and fossil energy. Finally, a shift in transport modes from car transport to more sustainable alternatives, such as bicycles and public transport will probably occur, especially in Belgium where traffic congestion is a major issue.

The above expected changes may influence the results obtained in this research to an important extent. To illustrate the potential influence of these future changes, two scenarios are defined, which are applied to the new variants of the analysed neighbourhood models. The first scenario (Future_electricity mix) assesses the impact of a (fictive) green electricity mix, consisting of 50% photovoltaic and 50% wind energy. In this scenario heat pumps are used for the heating and hot water production in buildings and fossil fuel cars are replaced by electric cars. The second scenario (Future_user transport) focuses on a shift to sustainable transport modes. In this scenario, the average transport profile for Flanders is adapted by assuming the following (fictive) distribution of the transport distances over the transport modes: 20% car transport, 40% public transport (20% by bus and 20% by train) and 40% bicycle transport. In contrary to the first scenario, the use of electric vehicles is not considered in the second scenario. The life cycle environmental costs of these future scenarios are shown in Figure 10.3. Compared to the current Belgian practice (Reference_new), the use of a green electricity mix results in a reduction of 30-35% of the life cycle environmental cost of the neighbourhood models. Slightly lower impact reductions of about 30% are obtained for a shift in transport modes.

Although the possibilities of the tool are illustrated in Chapter 8 by comparing representative schematic urban layouts, this last point illustrates that the developed tool allows a detailed quantitative analysis of creative designs (co-housing, transformable units, reusable elements…), in a changing economic environment (more circular economy, more sustainable energy mix, improved transport modes, …).

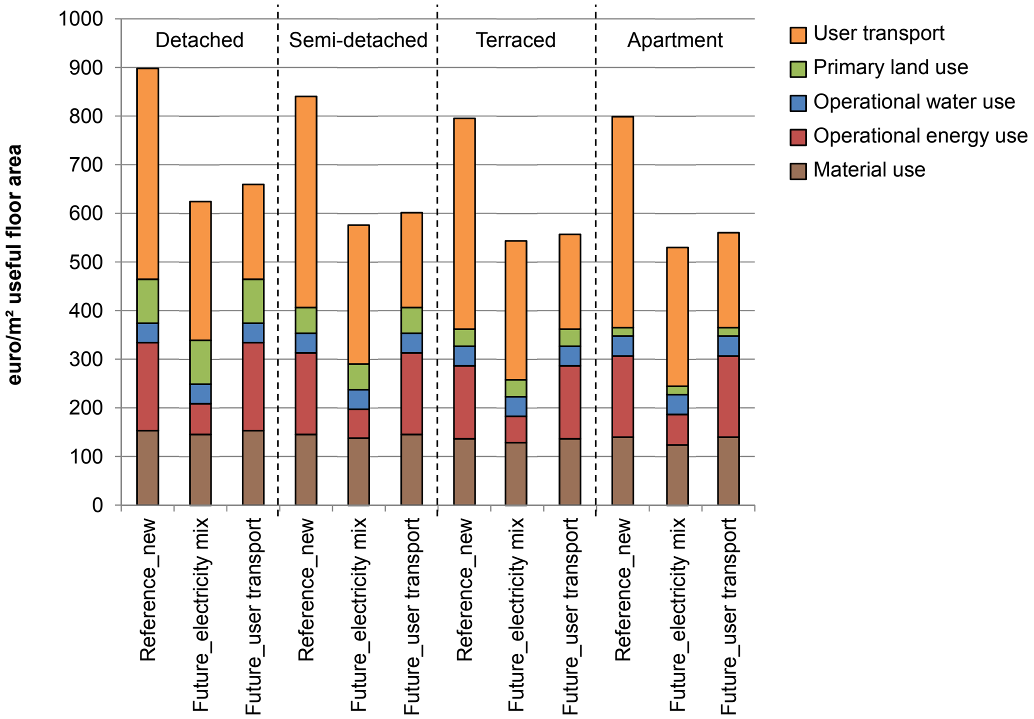

Figure 10.3: Life cycle environmental cost of the reference and future scenarios, subdivided per driver.

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Appendix A – Assessment issues in scoring tools for neighbourhoods

A.1 BREEAM Communities

Table A.1: Assessment issues and weighting in BREEAM Communities (BRE, 2016).

Assessment issues	Weighting (%)
GO – Governance	**9.3**
GO 01 – Consultation plan	2.3
GO 02 – Consultation and engagement	3.5
GO 03 – Design review	2.3
GO 04 – Community management of facilities	1.2
SE – Social and economic wellbeing	**42.7**
SE 01 – Economic impact	8.9
SE 02 – Demographic needs and priorities	2.7
SE 03 – Flood risk assessment	1.8
SE 04 – Noise pollution	1.8
SE 05 – Housing provision	2.7
SE 06 – Delivery of services, facilities and amenities	2.7
SE 07 – Public realm	2.7
SE 08 – Microclimate	1.8
SE 09 – Utilities	0.9
SE 10 – Adapting to climate change	2.7
SE 11 – Green infrastructure	1.8
SE 12 – Local parking	0.9
SE 13 – Flood risk management	1.8
SE 14 – Local vernacular	0.9
SE 15 – Inclusive Design	1.8
SE 16 – Light pollution	0.9
SE 17 – Training and skills	5.9
RE – Resources and energy	**21.7**
RE 01 – Energy strategy	4.1
RE 02 – Existing buildings and infrastructure	2.7
RE 03 – Water strategy	2.7
RE 04 – Sustainable buildings	4.1
RE 05 – Low impact materials	2.7
RE 06 – Resource efficiency	2.7
RE 07 – Transport carbon emissions	2.7
LE – Land use and ecology	**12.8**
LE 01 – Ecology strategy	3.2
LE 02 – Land use	2.1
LE 03 – Water pollution	1.1

Assessment issues	Weighting (%)
LE 04 – Enhancement of ecological value	3.2
LE 05 – Landscape	2.1
LE 06 – Rainwater harvesting	1.1
TM – Transport and movement	**13.8**
TM 01 – Transport assessment	3.2
TM 02 – Safe and appealing streets	3.2
TM 03 – Cycling network	2.1
TM 04 – Access to public transport	2.1
TM 05 – Cycling facilities	1.1
TM 06 – Public transport facilities	2.1
Inn – Innovation	**7**

A.2 CASBEE for Urban Development

Table A.2: Assessment issues and weighting in CASBEE for Urban Development (IBEC & JSBC, 2014).

Assessment issues	Weighting (%)
Q_{UD} Environmental quality of urban development	
Q 1 – Environment	**33.3**
Q 1.1 – Resource	
Q 1.1.1 – Water source	6.7
Q 1.1.2 – Resources recycling	6.7
Q 1.2 – Nature	
Q 1.2.1 – Greenery	6.7
Q 1.2.2 – Biodiversity	6.7
Q 1.3 – Artifact	
Q 1.3.1 – Environmentally considerate buildings	6.7
Q 2 – Society	**33.3**
Q 2.1 – Impartiality/Fairness	
Q 2.1.1 – Compliance	5.6
Q 2.1.2 – Area management	5.6
Q 2.2 – Security/Safety	
Q 2.2.1 – Disaster prevention	3.7
Q 2.2.2 – Traffic safety	3.7
Q 2.2.3 – Crime prevention	3.7
Q 2.3 – Amenity	
Q 2.3.1 – Convenience / welfare	5.6
Q 2.3.2 – Culture	5.6
Q 3 – Economy	**33.3**
Q 3.1 – Traffic/Urban structure	
Q 3.1.1 – Traffic	5.6
Q 3.1.2 – Urban structure	5.6

Assessment issues	Weighting (%)
Q 3.2 – Growth potential	
Q 3.2.1 – Population	5.6
Q 3.2.2 – Economic development	5.6
Q 3.3 – Efficiency and Rationality	
Q 3.3.1 – Information system	5.6
Q 3.3.2 – Energy system	5.6
L_{UD} Environmental load of urban development	
L 1 – Traffic sector	ton CO_2 /person.year
L 2 – Building sector	
L 3 – Greening sector	

A.3 DZM Wijken

Table A.3: Assessment issues and weighting in DZM Wijken (Vlaamse Overheid, 2017).

Assessment issues	Weighting (%)
KWA – Quality control	**14.0**
KWA 01 – Vision development	
KWA 01.01 – Inventory	1.6
KWA 01.02 – Vision for the site development	1.6
KWA 01.03 – Alternative vision	1.1
KWA 02 – Aesthetic and spatial qualities	
KWA 02.01 – Spatial quality	
KWA 02.02 – Plan for aesthetic quality	2.1
KWA 03 – Public support and participation	
KWA 03.01 – Stakeholders	1.3
KWA 03.02 – Participation	1.0
KWA 03.03 – Social entrepreneurship	0.6
KWA 03.04 – Financial feasibility	0.6
KWA 04 – Project management	
KWA 04.01 – Planning and documentation	1.0
KWA 04.02 – Neighbourhood completion	1.6
KWA 04.03 – Sustainability control	1.6
W&W – Well-being & welfare	**14.0**
W&W 01 – Lively neighbourhood	
W&W 01.01 – Neighbourhood facilities depending on the context	-
W&W 01.02 – Diversity in housing provision	4.2
W&W 02 – Inclusive neighbourhood	
W&W 02.01 – Inclusive living	3.8
W&W 02.02 – Affordable housing	0.4
W&W 03 – Active neighbourhood	
W&W 03.01 – Employment	4.2

Assessment issues	Weighting (%)
W&W 04 – Management & adaptive capacity	
W&W 04.01 – Growth and shrinkage	0.5
W&W 04.02 – Temporary use	0.9
MOB – Mobility	**14.0**
MOB 01 – Proximity	
MOB 01.01 – Proximity to daily destinations	3.5
MOB 02 – Transport trips	
MOB 02.01 – 'STOP' mobility principle	3.2
MOB 02.02 – Access to public transport	1.4
MOB 02.03 – Transport facilities	4.6
MOB 03 – Preparation for transport management and maintenance	
MOB 03.01 – Transport information for future inhabitants, workers and visitors	1.1
MOB 03.02 – Adaptive capacity	0.4
FYS – Physical environment	**14.0**
FYS 01 – Land use	
FYS 01.01 – Location of the development	4.7
FYS 01.02 - Soil quality	0.9
FYS 02 – Area environment	
FYS 02.03 – Air quality	1.2
FYS 02.06 – Radiation risk	1.2
FYS 02.01 – Urban heat island	1.2
FYS 02.02 – Wind climate	1.2
FYS 02.04 – Solar access	1.2
FYS 02.05 – Noise	0.6
FYS 02.07 – Light pollution	0.6
FYS 03 – Adaptive capacity	
FYS 03.01 – Adaptive capacity	1.4
GRN – Green & nature development	**14.0**
GRN 01 – Natural values	
GRN 01.01 – Natural values	7.0
GRN 02 – Benefits of greenery	
GRN 02.01 – Benefits of greenery	3.5
GRN 03 – Maintenance and adaptive capacity	
GRN 03.01 – Preparation management and maintenance	2.9
GRN 03.02 – Adaptive capacity	0.6
WAT – Water	**10.0**
WAT 01 – Site potential and limitations	
WAT 01.01 – Flood risk	0.4
WAT 01.02 – Site assessment	0.6
WAT 02 – Project water performance	
WAT 02.01 – Water use	1.5
WAT 02.02 – Rain water management	3.0

Assessment issues	Weighting (%)
WAT 02.03 – Waste water management	0.5
WAT 02.04 – Groundwater	0.5
WAT 03 – Preparation water management and maintenance	
WAT 03.01 – Management of water system	0.9
WAT 03.02 – Maintenance friendliness	0.6
WAT 04 – Climate and water robustness	
WAT 04.01 – Climate robustness of water system	0.8
WAT 04.02 – Water robustness	1.2
MAT – Materials	**10.0**
MAT 01 – Reuse of structures, buildings, building elements and materials	
MAT 01.01 – Reuse of structures in the collective space	1.7
MAT 01.02 – Reuse of existing buildings, building elements and materials	1.7
MAT 01.03 – Closed soil balance	1.1
MAT 02 – Environmental load of new materials and products	
MAT 02.01 – Environmental impact of building materials in the collective space	2.1
MAT 02.02 – Environmental impact of building materials in buildings	1.4
MAT 03 – Material and waste management	
MAT 03.02 – Waste management	1.3
MAT 03.01 – Material management	0.7
ENE B – Energy (detailed method)	**10.0**
ENE B.01 – Reduction of energy consumption	
ENE B.01.01 – Reduction of net energy demand of the neighbourhood	3.0
ENE B.01.02 – Renewable energy efficient microgrid	1.5
ENE B.01.03 – Non- renewable primary final energy consumption of the neighbourhood	3.0
ENE B.02 – Preparation for flexible extension	
ENE B.02.01 – Preparations renewable energy	1.8
ENE B.02.02 – Preparations thermal network	0.8
INN – Innovation	**5.0**
INN 01 – Innovation	
INN 01.01 – Proposed innovations	5.0

A.4 DGNB New Urban Districts

Table A.4: Assessment issues and weighting in DGNB New Urban Districts (DGNB GmbH, 2012).

Assessment issues	Weighting (%)
ENV – Environmental quality	**22.5**
ENV10 – Impact on the global and local environment	
ENV1.1 – Life Cycle Assessment	2.7
ENV1.2 – Water and soil protection	1.8
ENV1.3 – Change in urban climate	2.7
ENV1.4 – Biodiversity and integration	1.8

Assessment issues	Weighting (%)
ENV1.5 – Consideration of possible environmental effects	1.8
ENV20 – Use of resources and waste accumulation	
ENV2.1 – Land use	2.7
ENV2.2 – Total primary energy demand and proportion of renewable primary energy	2.7
ENV2.3 – Energy efficient building structure	1.8
ENV2.4 – Resource saving infrastructure	1.8
ENV2.5 – Local food production	0.9
ENV2.6 – Water cycle system	1.8
ECO – Economic quality	**22.5**
ECO10 – Life Cycle Costing	
ECO1.1 – Life Cycle Costing	6.8
ECO1.2 – Fiscal impact on the municipality	4.5
ECO20 – Value development	
ECO2.1 – Value stability	4.5
ECO2.2 – Space efficiency	6.8
SOC – Socio-cultural and functional quality	**22.5**
SOC10 – Social qualities	
SOC1.1 – Social and functional mix	1.8
SOC1.2 – Social and profit oriented infrastructure	1.8
SOC20 – Health, comfort and user satisfaction	
SOC2.1 – Objective / subjective security	1.8
SOC2.2 – Sojourn quality in public spaces	1.8
SOC2.3 – Noise prevention	1.8
SOC30 – Functionality	
SOC3.1 – Open space supply	2.7
SOC3.2 – Accessibility	1.8
SOC3.3 – Use flexibility and building structure	1.8
SOC40 – Creative quality	
SOC4.1 – Urban integration	2.7
SOC4.2 – Urban design	1.8
SOC4.3 – Use of existing building and structure	1.8
SOC4.4 – Art in public space	0.9
TEC – Technical quality	**22.5**
TEC10 – Technical infrastructure	
TEC1.1 – Energy technique	2.6
TEC1.2 – Efficient waste management	2.6
TEC1.3 – Rain water management	4.0
TEC1.4 – Information and telecommunication infrastructure	1.3
TEC20 – Technical quality	
TEC2.1 – Maintenance, cleaning	2.6
TEC30 – Transport, mobility	
TEC3.1 – Quality of traffic system	4.0

Assessment issues	Weighting (%)
TEC3.2 – Quality of street infrastructure	1.3
TEC3.3 – Quality of public transport infrastructure	1.3
TEC3.4 – Quality of cycling infrastructure	1.3
TEC3.5 – Quality of pedestrian infrastructure	1.3
PRO – Process quality	**10.0**
PRO10 – Participation	
PRO1.1 – Participation	1.7
PRO20 – Planning quality	
PRO2.1 – Process to concept finding	1.1
PRO2.2 – Integral planning	1.7
PRO2.3 – Municipal cooperation	1.1
PRO30 – Quality of building execution and completion	
PRO3.1 – Supervision	1.1
PRO3.2 – Building site, building process	1.1
PRO3.3 – Commercialisation	1.1
PRO3.4 – Quality control and monitoring	1.1

A.5 Strategies Sustainable Building Flanders

Table A.5: Assessment issues and weighting in Strategies Sustainable Building Flanders (Vandevyvere, 2010).

Assessment issues	Weighting (%)
M – Environmental sustainability	**37.5**
M1 – Material	4.9
M2 – Energy	8.6
M3 – Water	5.5
M4 – Land use	7.1
M5 – Mobility	6.7
M6 – Emissions and nuisance	4.6
E – Economic sustainability	**18.1**
E1 – Life Cycle Cost	5.2
E2 – Economic embeddedness	4.3
E3 – Juridical security	4.3
E4 – Future value	4.3
S – Socio-cultural sustainability	**26.0**
S1 – Security	3.2
S2 – Operationality	4.0
S3 – Integration	3.6
S4 – Sociability	3.6
S5 – Future value	3.6
R1 – Spatial quality	4.7

R2 – Identity	3.5
I – Process	**18.5**
I1 – Process quality	6.6
I2 – Participation	6.6
I3 – Integrity	5.3

Appendix B – Modelling of life cycle scenarios

Compared to the existing calculation model developed in the MMG and SuFiQuaD research projects (Allacker, 2010; Allacker, Debacker, et al., 2013), the life cycle scenarios have been thoroughly refined to model refurbishment activities and improve the calculation of periodic interventions. These scenarios are described in the subsequent sections.

B.1 Scenarios for refurbishment

In the existing SuFiQuaD method, which focused on the assessment of new buildings, the life cycle of building components was modelled in a static way, considering the same year of initial construction and EOL for all building components. Concretely, it was assumed that, apart from the necessary replacements, the same building components are used over the whole building life cycle. However, in the context of a refurbishment, more dynamic processes can occur including the demolition of existing building components and the addition of new building components. To model these processes, two additional parameters are implemented in the calculation model: the date of initial construction (*dN*) and the date of EOL (*dEOL*). These parameters are defined for each composed object at the various scale levels, i.e. at the level of the work sections (*dN_WS* and *dEOL_WS*), building elements (*dN_EL* and *dEOL_EL*) and buildings (*dN_BU* and *dEOL_BU*)[1]. Based on these parameters, a variety of life cycle scenarios can be assessed[2]. Three examples are given below:

- An existing building component in the context of a refurbishment is modelled by defining a date of initial construction in the past.
- A future change in the building layout requiring the addition of new building elements is modelled by defining building elements with a date of initial construction in future.
- The demolition of a building component in the context of a refurbishment is modelled by defining a date of EOL prior to the EOL of the building.

Depending on the entered parameters, the impacts of the initial construction and EOL of work sections are allocated to various life cycle modules. This is illustrated in Figure B.1 and Figure B.2. By convention, *dN* and *dEOL* are expressed in years, compared to the reference year 0, which is the start year of the analysis. A negative number of years refers to an intervention in the past (before the period of analysis). A positive number of years refers to a future intervention (after the start year of the analysis). As an example, a building component with a *dN* of -10 and *dEOL* of 60 was built 10 years ago and will be demolished in 60 years, starting from year 0.

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[1] Similar parameters could also be defined at the neighbourhood level. However, in this research, the neighbourhood life span was assumed to be equal to the life span of the constituting buildings.

[2] A current limitation is the automatic replacement of building components which have reached the end of their service life. However, in the context of a refurbishment, the life span of existing building components, which are still functioning well, can be extended further than the initial predicted life span.

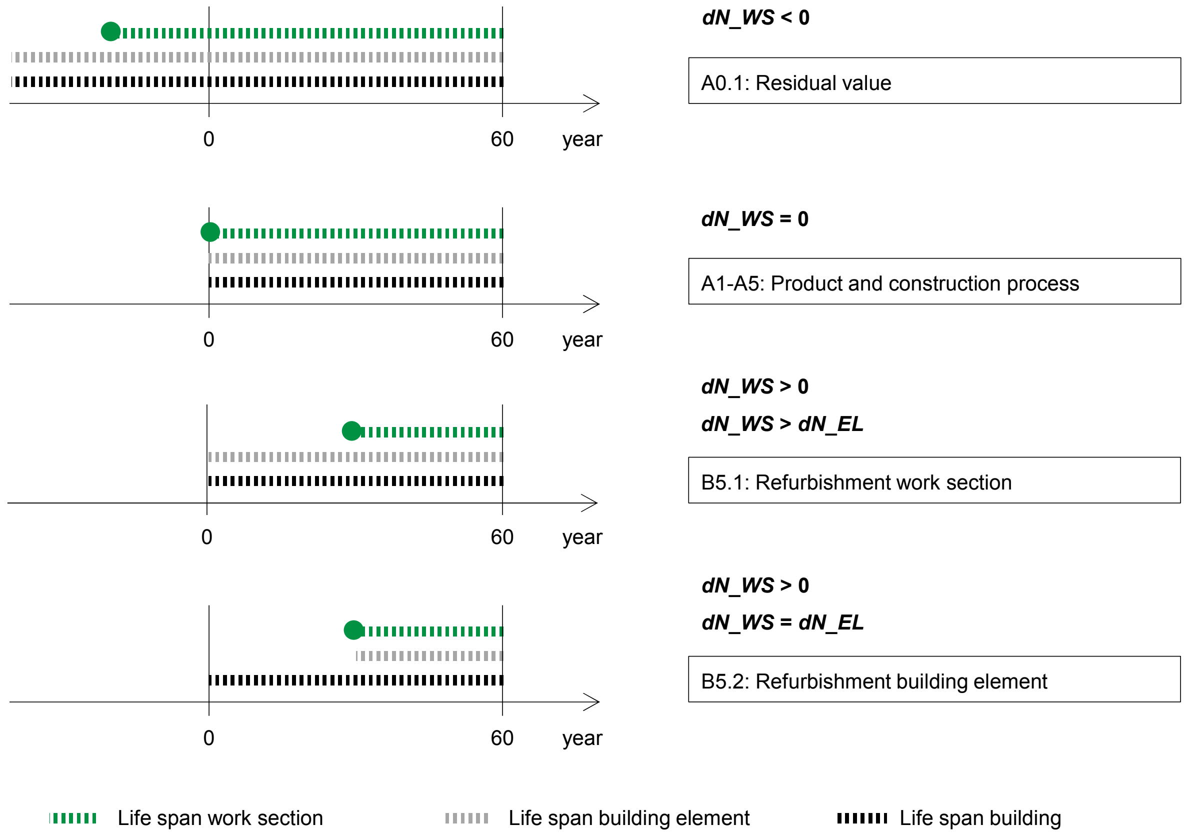

Figure B.1: Allocation of the initial construction impact of a work section to the life cycle modules. The year of construction of the work section is represented by a green dot.

Concerning the allocation of the initial construction impact of a work section (Figure B.1), three options are possible:

1. *dN_WS* < 0

   The work section is an existing building component, built in the past. A residual impact is calculated and allocated to module "A0.1: Residual value".

2. *dN_WS* = 0

   The work section is built at the start of the analysis (year 0). The impact of the initial construction is allocated to modules A1 up to A5 (production and construction process).

3. *dN_WS* > 0

   The work section will be built during a future refurbishment. If the date of the initial construction of the work section differs from the building element (in which the work section is included), the impact is allocated to module "B5.1: Refurbishment work section". Otherwise it is allocated to module "B5.2: Refurbishment building element".

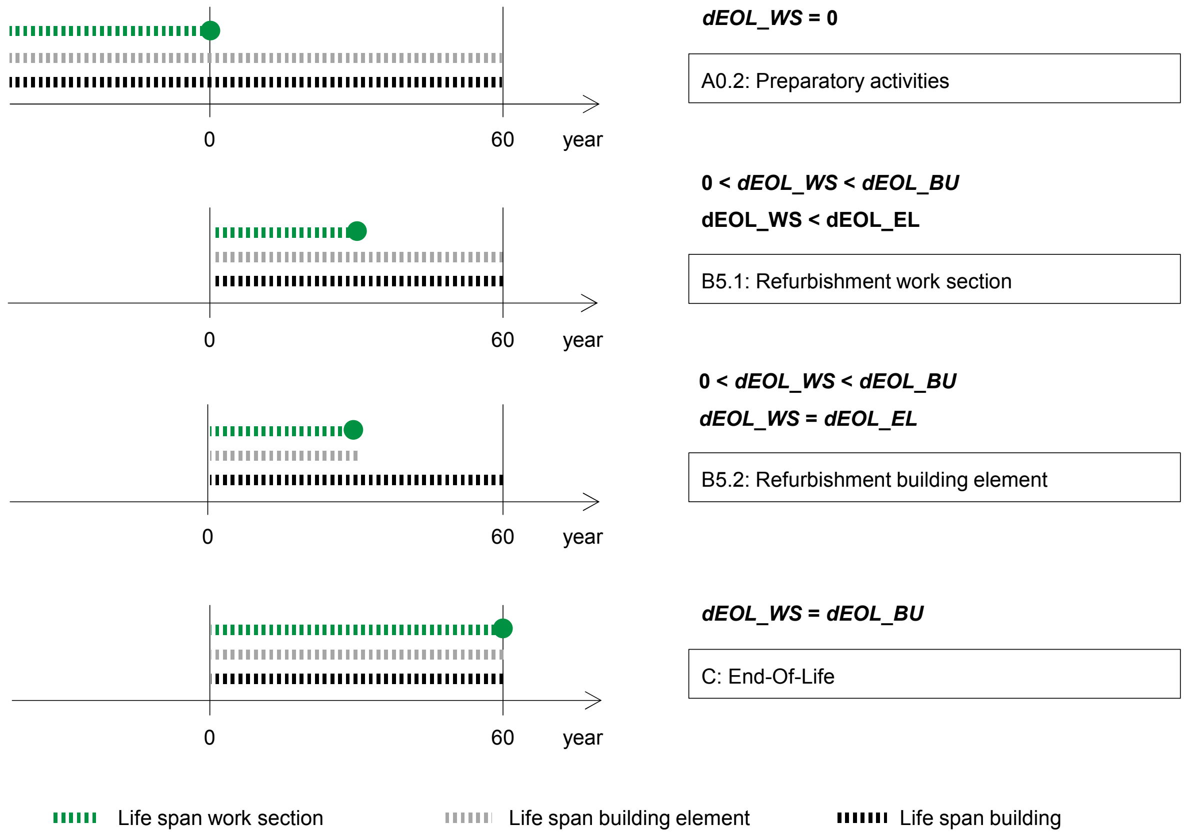

Figure B.2: Allocation of the EOL impact of a work section to the life cycle modules. The year of EOL of the work section is represented by a green dot.

Concerning the allocation of the EOL impact (Figure B.2), three options are possible:

1. *dEOL_WS* = 0

   The work section is an existing building component, which is demolished at year 0. The EOL impact is allocated to module "A0.2: Preparatory activities".

2. 0 < *dEOL_WS* < *dEOL_BU*:

   The work section will be demolished during a future refurbishment. If the date of the demolition of the work section differs from the building element (in which the work section is included), the impact is allocated to module "B5.1: Refurbishment work section". Otherwise it is allocated to module "B5.2: Refurbishment building element".

3. *dEOL_WS* = *dEOL_BU*

   The work section which will be demolished at the end of the building life cycle. The EOL impact is allocated to module C (End-of-Life stage).

B.2 Scenarios for periodic interventions

Various periodic interventions occur during the building life span, including maintenance processes (module B2), replacements (module B4) and periodic refurbishments (module B5). All these interventions should be modelled together as they interact with each other. For example, the replacement of a building component influences the necessity to carry out a maintenance process.

To deal with these interactions, a hierarchy is defined for the periodic interventions (Figure B.3), assuming that interventions at different levels in the hierarchy do not occur simultaneously. This hierarchy starts at the top with the refurbishment of the building element, followed by the replacement of the building element, refurbishment of the work section, replacement of the work section, big maintenance and finally small maintenance[3]. Priority is given to interventions which are higher in the hierarchy. For example, if a work section is replaced, big and small maintenance will not occur during the year of the replacement. Furthermore, the occurrence of an intervention depends on the frequency (*f*) of that intervention and of all interventions above in the hierarchy. These principles are illustrated based on two examples. In the first example (Figure B.4), periodic interventions are modelled without hierarchy resulting in a number of simultaneous interventions. In the second example (Figure B.5), this issue is solved by applying the proposed hierarchy and priority rules.

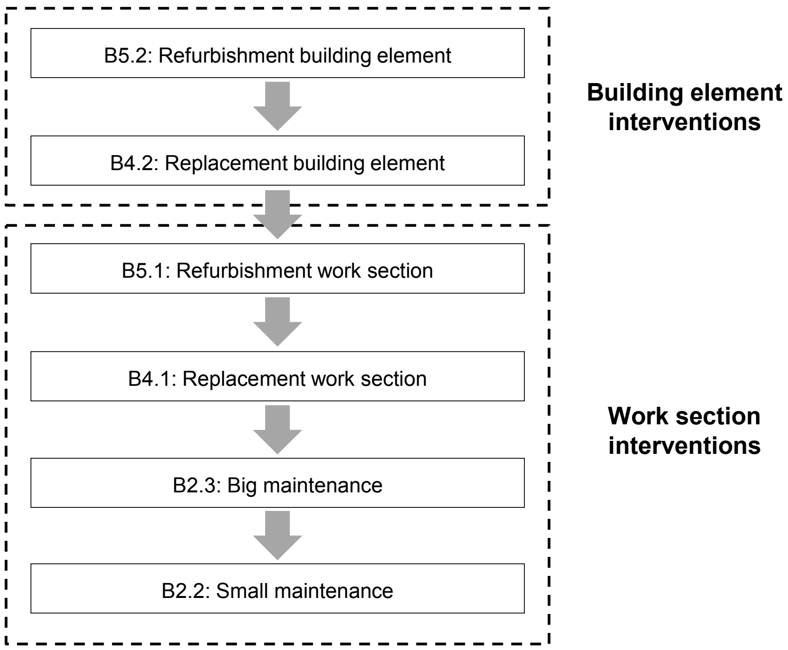

Figure B.3: Hierarchy of periodic interventions. A distinction is made between interventions at the level of the building elements and work sections.

[3] Cleaning processes are not included in the hierarchy as they occur every year, independently of other interventions.

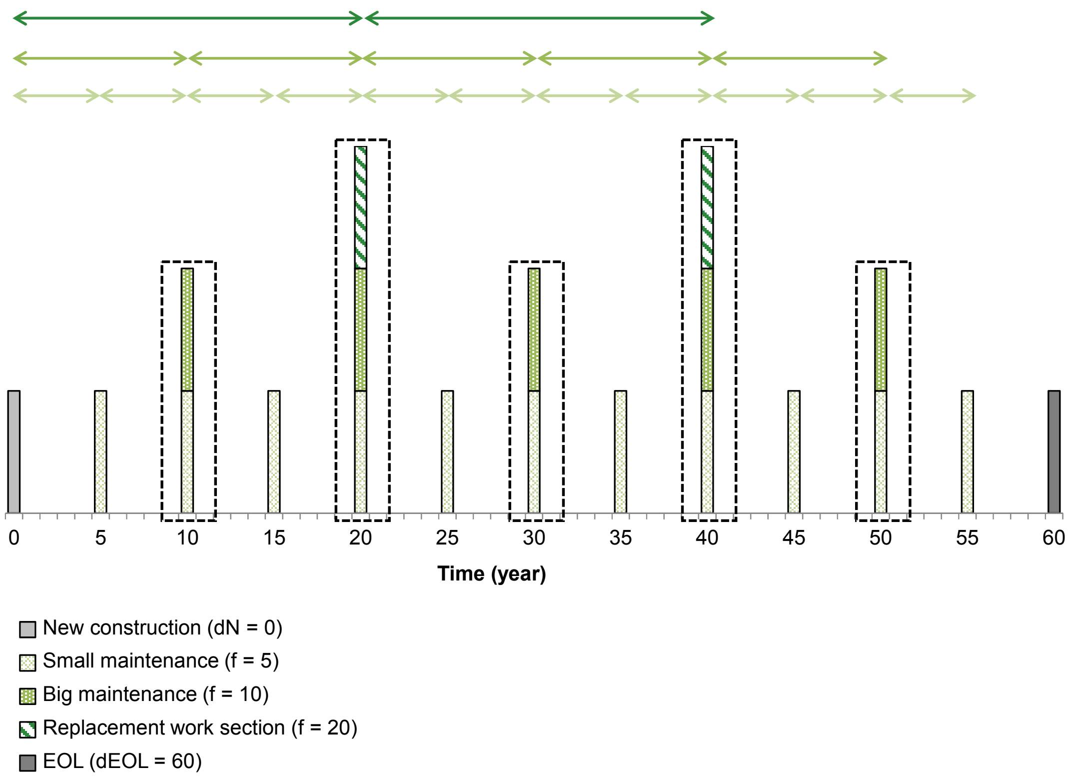

Figure B.4: Periodic interventions modelled without hierarchy. The occurrence of an intervention only depends on the frequency (*f*) of that intervention, resulting in simultaneous interventions (indicated by dotted frames).

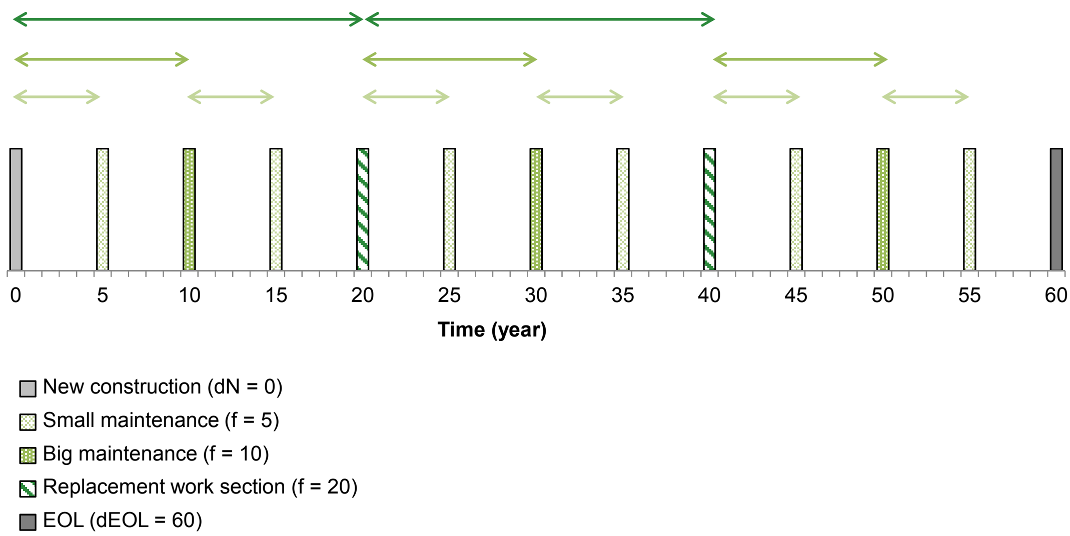

Figure B.5: Periodic interventions modelled with a hierarchy. The occurrence of an intervention depends on the frequency (*f*) of that intervention and of all interventions above in the hierarchy.

For each type of intervention three parameters are defined at the level of the works sections or building elements[4]:

- Frequency of intervention (*f*)

  This parameter indicates the expected number of years between two interventions.

- Suspension period (*s*)

  The suspension period is the minimum number of years separating the intervention from interventions higher in the hierarchy. This parameter is added to avoid the occurrence of several interventions in years close to each other, which is not desirable in practice (e.g. the replacement of a window, a few years before the demolition of the building). The concept of suspension period is illustrated based on two examples. In the first example (Figure B.6), periodic interventions are modelled without suspension period, resulting in several interventions occurring in years close to each other. In the second example (Figure B.7), this issue is solved by applying a suspension period for each periodic intervention.

- Date of the most recent intervention (*r*)

  This parameter is used to define the start year of the periodic cycles of each intervention. As a default, all periodic cycles are starting at year 0. However, in the context of a refurbishment, interventions can have taken place in the past. In that case the date of the most recent intervention (indicated by a negative number of years compared to year 0) can be used as start year for the calculation of the periodic cycles.

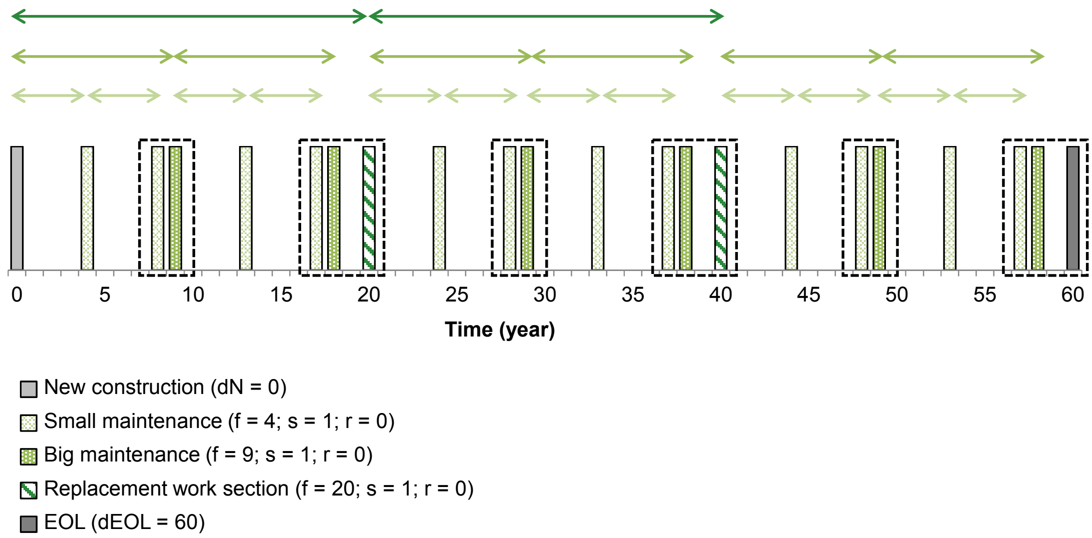

Figure B.6: Periodic interventions modelled without a suspension period (s = 1). A number of interventions occur within an interval of 1 to 2 years from each other (indicated by dotted frames).

[4] The distinction between interventions at the level of the work sections and at the level of the building elements is illustrated in Figure B.3.

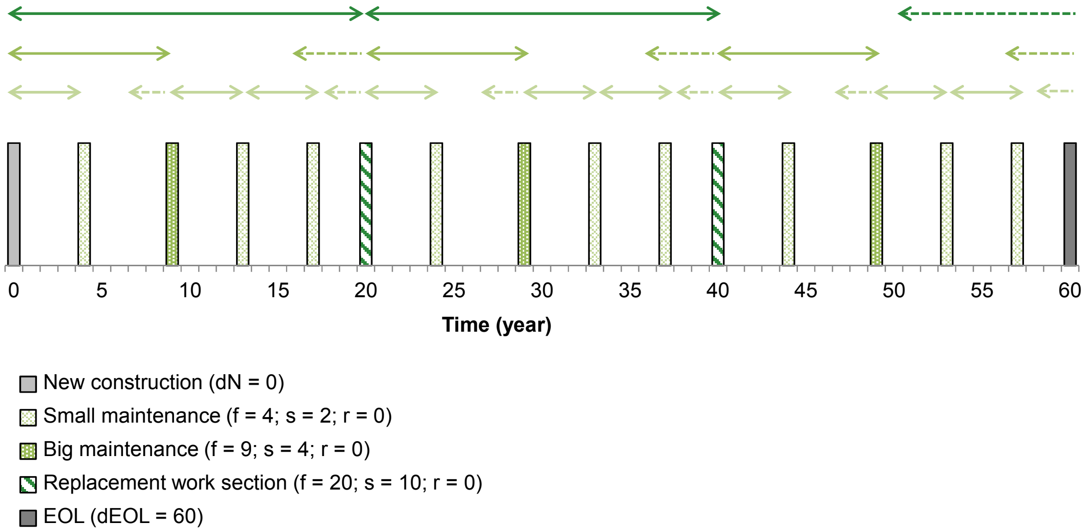

Figure B.7: Periodic interventions modelled with a suspension period (indicated by dotted arrows).

Appendix C – Building and neighbourhood geometry parameters

C.1 Building geometry

A simplified approach is developed to define the geometry of buildings during the master planning phase of neighbourhoods. This approach is necessary, because by hypothesis only the general layout and building geometry are known in that design stage. The following assumptions are used for the development of the approach:

1. The analysed buildings have a rectangular floor plan.[5]
2. All floors are identical.
3. No basement floor is considered.[6]

The approach is based on six main input parameters to define the whole building geometry (Figure C.1):

1. <u>Total floor area</u> (A_F): sum of the area of all floors. For apartment buildings, the total floor area is the sum of the floor area of the housing units (useful floor area) and the floor area of the shared circulation spaces.
2. <u>Total floor perimeter</u> (P_F): sum of the perimeters of all floors.
3. <u>Ground floor area</u> (A_{GF}) and <u>perimeter</u> (P_{GF}): area and perimeter of the ground floor.
4. <u>Storey height</u> (H_S) and <u>number of stories</u> (N_S). For the storey height a default value of 3 m for all floors is proposed.
5. <u>Average room area</u> (A_R). As the internal layout of the buildings is often unknown during the master planning phase, an average room area is defined to make an estimation of the amount of internal walls. A default value of 10 m² is proposed, calculated based on the minimum room area requirements defined by the Flemish Company for Social Housing (VMSW, 2008).
6. <u>Window to floor ratio</u> ($R_{W/F}$): ratio of the window area to the total floor area. A default value of 15% is proposed, based on the requirements of the Flemish Company for Social Housing (VMSW, 2008)[7].

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[5] The approach can easily be extended to other shapes. As the analysed schematic neighbourhood models only consists of rectangular buildings (see Chapter 8), this is not further discussed in this dissertation.

[6] The analysis of buildings with a basement is possible but requires additional input parameters.

[7] According to (VMSW, 2008), the window to floor ratio should be at least 1/6 for livings spaces and 1/8 for kitchens and bedrooms. In this research, 15% is assumed as average between both requirements.

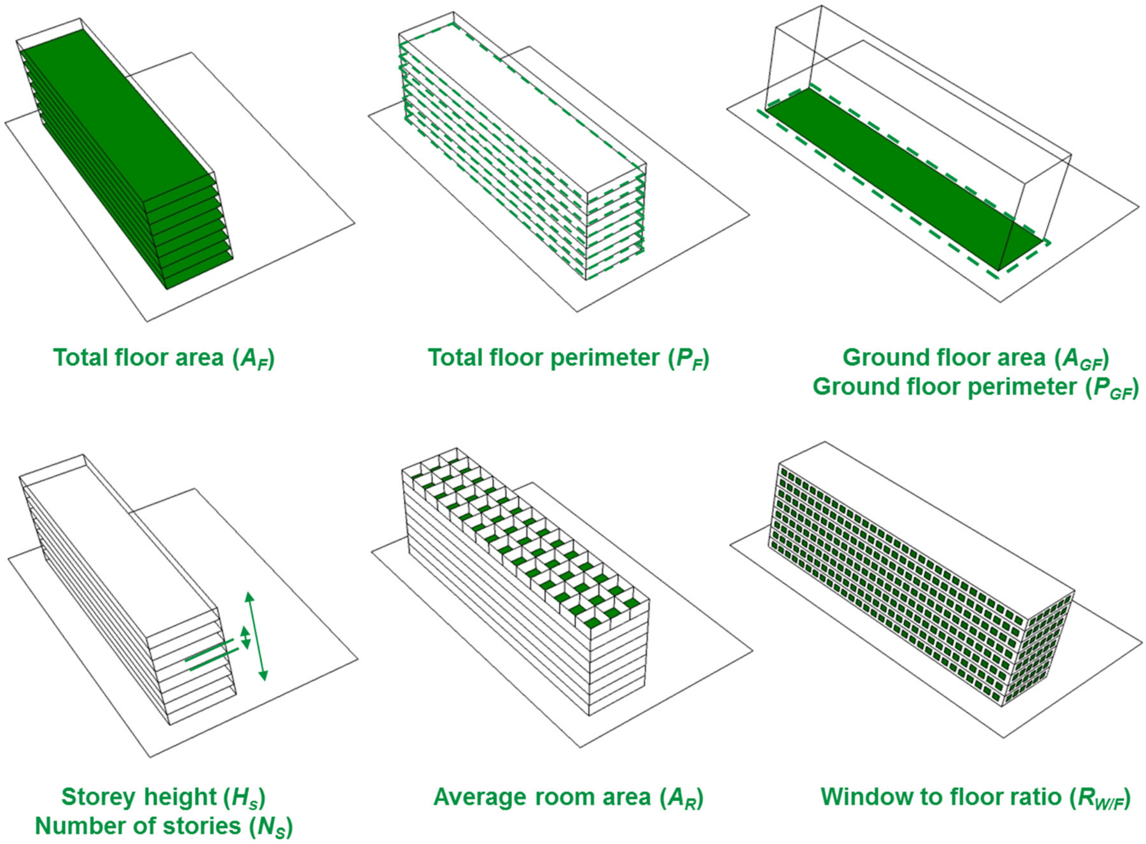

Figure C.1: Six main input parameters to define the building geometry.

Concerning the measuring conventions, the areas and dimensions are measured at the axis of the building elements (reference line for asymmetric cross sections) as the thickness of building elements is unknown during the master planning stage. This measuring convention was also selected in the SuFiQuaD research project as it avoids the need for re-measuring when other technical solutions for the building elements are selected (Allacker, 2010).

Based on the six main input parameters, the amount of the various building elements is calculated. The formulas and assumptions used for each building element are described in the subsequent paragraphs.

(13)+ floor on grade

The area of the floor on grade (A_{FG}) is equal to the ground floor area (A_{GF}) (Formula [C.1]):

$$A_{FG} = A_{GF} \quad [C.1]$$

(16)+ foundation

The foundation length (L_F) is calculated as the sum of the foundation length under the external walls (L_{FE}) and under the load-bearing internal walls (L_{FI}) (Formula [C.2]):

$$L_F = L_{FE} + L_{FI} \quad [C.2]$$

The foundation length under the external walls (L_{FE}) is equal to the perimeter of the ground floor (P_{GF}) (Formula [C.3]):

$$L_{FE} = P_{GF} \qquad [C.3]$$

The foundation length under the load-bearing internal walls (L_{FI}) is calculated using Formula [C.4], making an estimation of the length of the load-bearing internal walls for the ground floor area (A_{GF}). This formula is based on the approach defined for the calculation of the length of internal walls (see below), assuming a distribution of 50% load-bearing and 50% non-load-bearing internal walls:

$$L_{FI} = 50\% \times \left(\frac{4A_{GF}}{\sqrt{A_R}} - P_{GF} \right) \Big/ 2 \qquad [C.4]$$

(21)+ external wall

The area of external walls (A_{EW}) is calculated by multiplying the total floor perimeter (P_F) with the storey height (H_s) and by subtracting the area of window openings (A_{WO}) (Formula [C.5]).

$$A_{EW} = P_F H_S - A_{WO} \qquad [C.5]$$

The area of window openings (A_{WO}) is calculated by multiplying the window to floor ratio ($R_{W/F}$) with the total floor area (A_F) (Formula [C.6]):

$$A_{WO} = R_{W/F} A_F \qquad [C.6]$$

(22)+ internal wall

To calculate the amount of internal walls, each floor is subdivided in a number of square rooms with an area equal to the average room area (A_R). This is illustrated in Figure C.2. Based on this subdivision, the following relationship can be written between the total floor area (A_F), the average room area (A_R), the total floor perimeter (P_F), and the length of internal walls (L_{IW}) (Formula [C.7]):

$$P_F + 2L_{IW} = \frac{A_F}{A_R} \times 4 \times \sqrt{A_R} \qquad [C.7]$$

With:

- $\frac{A_F}{A_R}$ = number of square rooms with area A_R that fits within the total floor area A_F
- $\sqrt{A_R}$ = length (m) of one side of a square room with area A_R

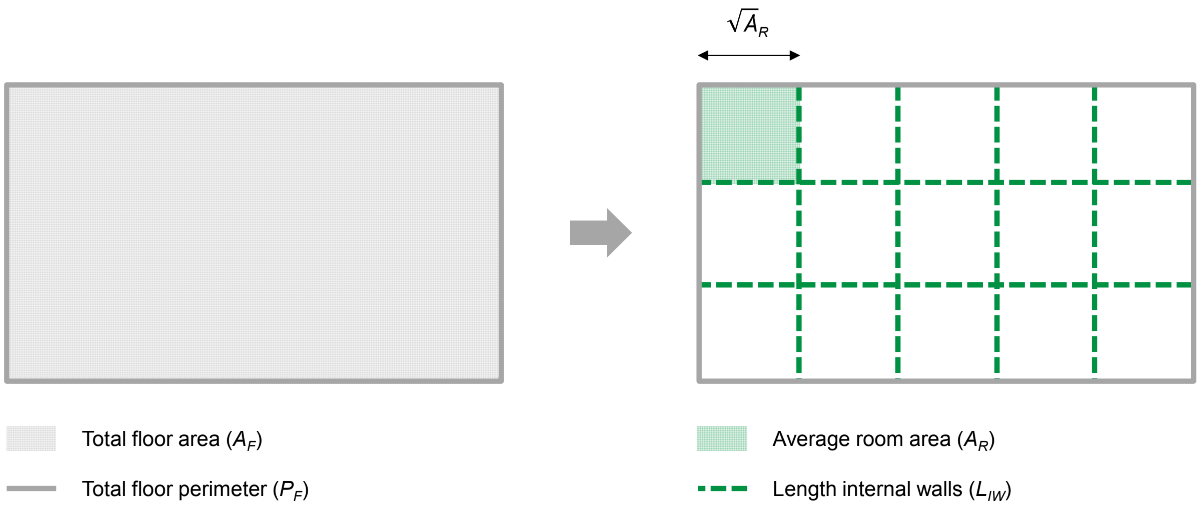

Figure C.2: Calculation of the amount of internal walls.

By rearranging the equation, the length of internal walls (L_{IW}) can be calculated as follows (Formula [C.8])[8]:

$$L_{IW} = \left(\frac{4A_F}{\sqrt{A_R}} - P_F \right) \Big/ 2 \qquad [C.8]$$

The area of internal walls (A_{IW}) is then obtained by multiplying the total length of internal walls (L_{IW}) with the storey height (H_S) and by subtracting the area of door openings (A_{DO}) (Formula [C.9]).

$$A_{IW} = L_{IW} H_S - A_{DO} \qquad [C.9]$$

The area of internal walls is further subdivided in load-bearing and non-load-bearing internal walls. As default, a distribution of 50% load-bearing and 50% non-load-bearing internal walls is assumed.

The area of door openings (A_{DO}) is calculated by multiplying the number of doors by the area per door opening. The number of internal doors (N_{ID}) is assumed to be equal to the number of rooms (Formula [C.10]):

$$N_{ID} = \frac{A_F}{A_R} \qquad [C.10]$$

(23)+ storey floor

The area of storey floors (A_{SF}) is calculated as the total floor area (A_F) minus the area of the ground floor (A_{GF}) and the area of openings for stairs (A_{SO}), using Formula [C.11]. The area of

[8] In case the building width and depth are not an exact multiple of the average square room side ($\sqrt{A_R}$), the formula is still used as approximation.

openings for stairs is calculated by multiplying the number of stairs (see “(24)+ stairs”) by the opening area per stairs.

$$A_{SF} = A_F - A_{GF} - A_{SO} \tag{C.11}$$

(24)+ stairs

For single family houses, the number of stairs (N_{ST}) is calculated as the number of storeys (N_S) minus one (Formula [C.12]):

$$N_{ST} = N_S - 1 \tag{C.12}$$

For apartment buildings, the number of stairs (N_{ST}) is calculated as the number of storeys (N_S) minus one, multiplied by the number of circulation cores (N_{CC}).

$$N_{ST} = (N_S - 1) \times N_{CC} \tag{C.13}$$

(27.1)+ flat roof[9]

The area of the flat roof (A_{FR}) is equal to the ground floor area (A_{GF}) (Formula [C.14]):

$$A_{FR} = A_{GF} \tag{C.14}$$

(31) windows

The window area (A_{WO}) is calculated based on Formula [C.6] (see “(21)+ external wall”).

(32) internal doors

The number of internal doors (N_{ID}) is based on Formula [C.10] (see “(22)+ internal wall”).

(5) piped services

As the layout of the technical installations in buildings is often unknown during the master planning phase, default values for the ratios of piped services have been defined based on data from the SuFiQuaD project (Allacker, 2010; Allacker, De Troyer, et al., 2013). Other default values are used for single family houses and apartment buildings because important ratio differences are noticed between both housing types.

(6) electrical services

The same approach as for the piped services is followed. Default values for the ratios of electrical services have been defined based on data from the SuFiQuaD project, including a distinction between single family houses and apartment buildings.

[9] The approach is developed for buildings with a flat roof but could be easily extended to buildings with a pitched roof as the amount of pitched roof is expressed in m² of horizontal projected area.

C.2 Neighbourhood geometry

To define the neighbourhood geometry, input parameters are required for the buildings, networks and open spaces (Figure C.3).

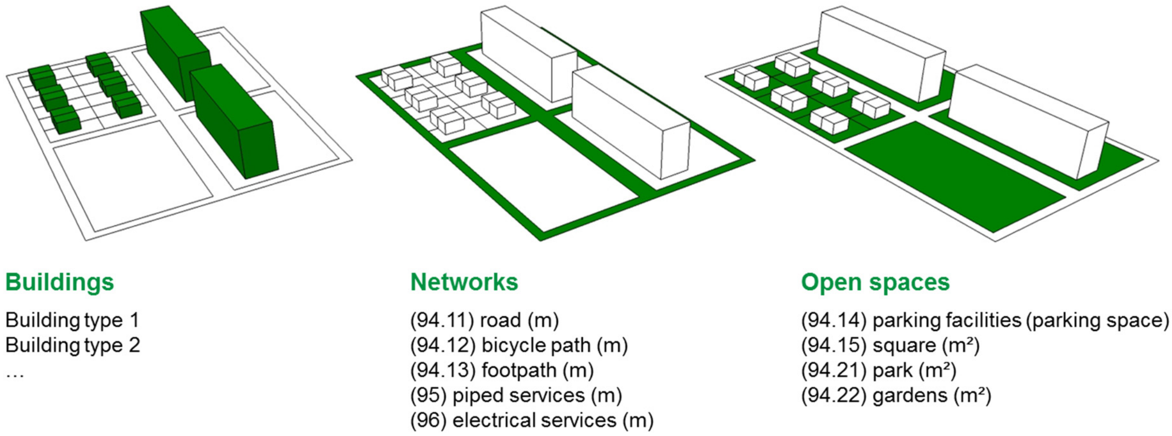

Figure C.3: Definition of the neighbourhood geometry. Parameters are entered for the buildings, networks and open spaces.

Buildings

The geometry of the buildings is fully defined at the building level (see section C.1). At the neighbourhood level, the number of buildings of each type is entered.

Networks

The networks are defined by entering the length of each network. This includes the following external elements:

- road infrastructure: (94.11) road, (94.12) bicycle path and (94.13) footpath.
- utilities: (95) piped services and (96) electrical services.

Open spaces

The open spaces are defined by entering the area of each open space. This includes the following external elements:

- paved areas: (94.14) parking facilities[10] and (94.15) squares.
- planted areas: (94.21) park and (94.22) gardens.

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[10] For the parking facilities, the number of provided parking spaces is entered instead of the area of the facility. This alternative functional unit is selected as it allows for a meaningful comparison between various parking variants such as parking drives, street parking and parking lots, which result in another amount of additional circulation (see Chapter 7).

Appendix D – Score calculation for the sustainability measures

In this appendix, the detailed calculation of the BREEAM, DZM Wijken and DGNB scores is reported for the reference new neighbourhoods and the sustainability measures. To simplify the analysis only the assessment issues which are influenced by the analysed sustainability measures and variations in urban layout and built density have been considered. For the sustainability measures, the score increase or reduction compared to the reference new neighbourhood is mentioned in a separate column (ΔREF) and indicated with a red to green colour scale (Figure D.1).

The calculation of the score is illustrated based on an example (Figure B.2). In BREEAM Communities, the reference new variant of the detached house model obtains 1.4 percentage points for the assessment issue “RE 05 – Low impact materials” as more than 80% of the volume of materials used in the public realm achieve an A+ to B rating. When recycled materials are used for the paved areas, 2.7 percentage points are assigned as an additional criterion is fulfilled (more than 30% of the volume of road construction materials is constituted from recycled material). The score increase (+1.4 percentage points) is then calculated as the difference between the score of the sustainability measure and the score of the reference new variant.

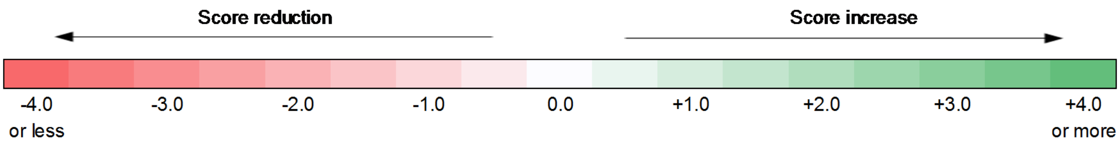

Figure D.1: Red to green colour scale used to indicate the score increases and reductions compared to the reference new neighbourhoods.

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
Reference_new	RE 05 – Low impact materials	More than 80% of the volume of materials used in the public realm achieve an A+ to B rating	1.4	
M2_recycled materials	RE 05 – Low impact materials	More than 80% of the volume of materials used in the public realm achieve an A+ to B rating More than 30% of the volume of road construction materials is reclaimed or constituted from recycled material	2.7	+1.4

Figure D.2: Calculation of the BREEAM score for the sustainability measure “M2_recycled materials” (Model 1_detached)

Sustainaibility measures	Assessment issues	Description	Score (%)
Reference_new	SE 11 – Green infrastructure	No public green infrastructure	0.0
	SE 13 – Flood risk management	Rainwater management (separate sewer and drainage ditches)	1.8
	RE 01 – Energy strategy	Reduction in CO2 emissions of 12.8% compared to the baseline energy demand	0.7
	RE 05 – Low impact materials	More than 80% of the volume of materials used in the public realm achieve an A+ to B rating	1.4
	LE 02 – Land use	No credit since the neighbourhood is assumed to be built on forest land	0.0
	LE 04 – Enhancement of ecological value	No enhancement of the ecological value	0.0
	LE 06 – Rainwater harvesting	83% of the total hard surface is used for rainwater harvesting	1.1
	TM 03 – Cycling network	No cycling infrastructure	0.0
	TM 04 – Access to public transport	The public transport stop is located at 750 m and the service frequency fulfils the requirements for rural areas	1.6
		TOTAL	**6.6**

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
M1_timber	-	The impact of the materials used in buildings is not evaluated	0.0	0.0
M2_recycled materials	RE 05 – Low impact materials	More than 80% of the volume of materials used in the public realm achieve an A+ to B rating	2.7	+1.4
		More than 30% of the volume of road construction materials is reclaimed or constituted from recycled material		
E1_non-insulated	RE 01 – Energy strategy	No reduction in CO2 emissions compared to the baseline energy demand	0.0	-0.7
E2_passive standard	RE 01 – Energy strategy	Reduction in CO2 emissions of 52.1% compared to the baseline energy demand	2.2	+1.5
E3_oil boiler	RE 01 – Energy strategy	No reduction in CO2 emissions compared to the baseline energy demand	0.0	-0.7
E4_heat pump	RE 01 – Energy strategy	Reduction in CO2 emissions of 39% compared to the baseline energy demand	1.9	+1.1
E5_no PV	RE 01 – Energy strategy	No reduction in CO2 emissions compared to the baseline energy demand	0.0	-0.7
W1_no rainwater tank	LE 06 – Rainwater harvesting	No rainwater harvesting	0.0	-1.1
W2_combined sewer	SE 13 – Flood risk management	No rainwater management (combined sewer)	0.0	-1.8
W3_permeable areas	SE 13 – Flood risk management	Rainwater management (permeable areas and drainage ditches)	1.8	0.0
L1_urban land	LE 02 – Land use	100% of the neighbourhood area is built on previously developed land	0.7	+0.7
L2_arable land	LE 02 – Land use	No credit for a development on arable land	0.0	0.0
L3_park	SE 11 – Green infrastructure	Public green infrastructure is provided within walking distance	1.8	+2.9
	LE 04 – Enhancement of ecological value	The park contributes to the enhancement of the ecological value	1.1	
T1_urban area	TM 04 – Access to public transport	The public transport stop is located at 50 m and the service frequency fulfils the requirements for urban areas	2.1	+0.5
T2_rural area	TM 04 – Access to public transport	The public transport stop is located at 1300 m and the service frequency fulfils the requirements for rural areas	0.5	-1.1
T3_bicycle path	TM 03 – Cycling network	Provision of bicycle paths	2.1	+2.1

Figure D.3: BREEAM scores for the reference new neighbourhood and the sustainability measures (Model 1_detached).

Sustainaibility measures	Assessment issues	Description	Score (%)
Reference_new	SE 11 – Green infrastructure	No public green infrastructure	0.0
	SE 13 – Flood risk management	Rainwater management (separate sewer and drainage ditches)	1.8
	RE 01 – Energy strategy	Reduction in CO2 emissions of 14.8% compared to the baseline energy demand	0.7
	RE 05 – Low impact materials	More than 80% of the volume of materials used in the public realm achieve an A+ to B rating	1.4
	LE 02 – Land use	No credit since the neighbourhood is assumed to be built on forest land	0.0
	LE 04 – Enhancement of ecological value	No enhancement of the ecological value	0.0
	LE 06 – Rainwater harvesting	83% of the total hard surface is used for rainwater harvesting	1.1
	TM 03 – Cycling network	No cycling infrastructure	0.0
	TM 04 – Access to public transport	The public transport stop is located at 750 m and the service frequency fulfils the requirements for rural areas	1.6
		TOTAL	**6.6**

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
M1_timber	-	The impact of the materials used in buildings is not evaluated	0.0	0.0
M2_recycled materials	RE 05 – Low impact materials	More than 80% of the volume of materials used in the public realm achieve an A+ to B rating	2.7	+1.4
		More than 30% of the volume of road construction materials is reclaimed or constituted from recycled material		
E1_non-insulated	RE 01 – Energy strategy	No reduction in CO2 emissions compared to the baseline energy demand	0.0	-0.7
E2_passive standard	RE 01 – Energy strategy	Reduction in CO2 emissions of 52.4% compared to the baseline energy demand	2.2	+1.5
E3_oil boiler	RE 01 – Energy strategy	No reduction in CO2 emissions compared to the baseline energy demand	0.0	-0.7
E4_heat pump	RE 01 – Energy strategy	Reduction in CO2 emissions of 39.4% compared to the baseline energy demand	1.9	+1.1
E5_no PV	RE 01 – Energy strategy	No reduction in CO2 emissions compared to the baseline energy demand	0.0	-0.7
W1_no rainwater tank	LE 06 – Rainwater harvesting	No rainwater harvesting	0.0	-1.1
W2_combined sewer	SE 13 – Flood risk management	No rainwater management (combined sewer)	0.0	-1.8
W3_permeable areas	SE 13 – Flood risk management	Rainwater management (permeable areas and drainage ditches)	1.8	0.0
L1_urban land	LE 02 – Land use	100% of the neighbourhood area is built on previously developed land	0.7	+0.7
L2_arable land	LE 02 – Land use	No credit for a development on arable land	0.0	0.0
L3_park	SE 11 – Green infrastructure	Public green infrastructure is provided within walking distance	1.8	+2.9
	LE 04 – Enhancement of ecological value	The park contributes to the enhancement of the ecological value	1.1	
T1_urban area	TM 04 – Access to public transport	The public transport stop is located at 50 m and the service frequency fulfils the requirements for urban areas	2.1	+0.5
T2_rural area	TM 04 – Access to public transport	The public transport stop is located at 1300 m and the service frequency fulfils the requirements for rural areas	0.5	-1.1
T3_bicycle path	TM 03 – Cycling network	Provision of bicycle paths	2.1	+2.1

Figure D.4: BREEAM scores for the reference new neighbourhood and the sustainability measures (Model 2_semidetached).

Sustainaibility measures	Assessment issues	Description	Score (%)
Reference_new	SE 11 – Green infrastructure	No public green infrastructure	0.0
	SE 13 – Flood risk management	Rainwater management (separate sewer and drainage ditches)	1.8
	RE 01 – Energy strategy	Reduction in CO_2 emissions of 17.7% compared to the baseline energy demand	1.1
	RE 05 – Low impact materials	More than 80% of the volume of materials used in the public realm achieve an A+ to B rating	1.4
	LE 02 – Land use	No credit since the neighbourhood is assumed to be built on forest land	0.0
	LE 04 – Enhancement of ecological value	No enhancement of the ecological value	0.0
	LE 06 – Rainwater harvesting	86% of the total hard surface is used for rainwater harvesting	1.1
	TM 03 – Cycling network	No cycling infrastructure	0.0
	TM 04 – Access to public transport	The public transport stop is located at 750 m and the service frequency fulfils the requirements for rural areas	1.6
		TOTAL	**6.9**

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
M1_timber	-	The impact of the materials used in buildings is not evaluated	0.0	0.0
M2_recycled materials	RE 05 – Low impact materials	More than 80% of the volume of materials used in the public realm achieve an A+ to B rating	2.7	+1.4
		More than 30% of the volume of road construction materials is reclaimed or constituted from recycled material		
E1_non-insulated	RE 01 – Energy strategy	No reduction in CO_2 emissions compared to the baseline energy demand	0.0	-1.1
E2_passive standard	RE 01 – Energy strategy	Reduction in CO_2 emissions of 52.4% compared to the baseline energy demand	2.2	+1.1
E3_oil boiler	RE 01 – Energy strategy	No reduction in CO_2 emissions compared to the baseline energy demand	0.0	-1.1
E4_heat pump	RE 01 – Energy strategy	Reduction in CO_2 emissions of 39.8% compared to the baseline energy demand	1.9	+0.7
E5_no PV	RE 01 – Energy strategy	No reduction in CO_2 emissions compared to the baseline energy demand	0.0	-1.1
W1_no rainwater tank	LE 06 – Rainwater harvesting	No rainwater harvesting	0.0	-1.1
W2_combined sewer	SE 13 – Flood risk management	No rainwater management (combined sewer)	0.0	-1.8
W3_permeable areas	SE 13 – Flood risk management	Rainwater management (permeable areas and drainage ditches)	1.8	0.0
L1_urban land	LE 02 – Land use	100% of the neighbourhood area is built on previously developed land	0.7	+0.7
L2_arable land	LE 02 – Land use	No credit for a development on arable land	0.0	0.0
L3_park	SE 11 – Green infrastructure	Public green infrastructure is provided within walking distance	1.8	+2.9
	LE 04 – Enhancement of ecological value	The park contributes to the enhancement of the ecological value	1.1	
T1_urban area	TM 04 – Access to public transport	The public transport stop is located at 50 m and the service frequency fulfils the requirements for urban areas	2.1	+0.5
T2_rural area	TM 04 – Access to public transport	The public transport stop is located at 1300 m and the service frequency fulfils the requirements for rural areas	0.5	-1.1
T3_bicycle path	TM 03 – Cycling network	Provision of bicycle paths	2.1	+2.1

Figure D.5: BREEAM scores for the reference new neighbourhood and the sustainability measures (Model 3_terraced).

Sustainaibility measures	Assessment issues	Description	Score (%)
Reference_new	SE 11 – Green infrastructure	No public green infrastructure	0.0
	SE 13 – Flood risk management	Rainwater management (separate sewer and drainage ditches)	1.8
	RE 01 – Energy strategy	Reduction in CO2 emissions of 8.1% compared to the baseline energy demand	0.4
	RE 05 – Low impact materials	More than 80% of the volume of materials used in the public realm achieve an A+ to B rating	1.4
	LE 02 – Land use	No credit since the neighbourhood is assumed to be built on forest land	0.0
	LE 04 – Enhancement of ecological value	No enhancement of the ecological value	0.0
	LE 06 – Rainwater harvesting	49% of the total hard surface is used for rainwater harvesting	0.7
	TM 03 – Cycling network	No cycling infrastructure	0.0
	TM 04 – Access to public transport	The public transport stop is located at 750 m and the service frequency fulfils the requirements for rural areas	1.6
		TOTAL	**5.8**

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
M1_timber	-	The impact of the materials used in buildings is not evaluated	0.0	0.0
M2_recycled materials	RE 05 – Low impact materials	More than 80% of the volume of materials used in the public realm achieve an A+ to B rating	2.7	+1.4
		More than 30% of the volume of road construction materials is reclaimed or constituted from recycled material		
E1_non-insulated	RE 01 – Energy strategy	No reduction in CO2 emissions compared to the baseline energy demand	0.0	-0.4
E2_passive standard	RE 01 – Energy strategy	Reduction in CO2 emissions of 36% compared to the baseline energy demand	1.5	+1.1
E3_oil boiler	RE 01 – Energy strategy	No reduction in CO2 emissions compared to the baseline energy demand	0.0	-0.4
E4_heat pump	RE 01 – Energy strategy	Reduction in CO2 emissions of 26.1% compared to the baseline energy demand	1.1	+0.7
E5_no PV	RE 01 – Energy strategy	No reduction in CO2 emissions compared to the baseline energy demand	0.0	-0.4
W1_no rainwater tank	LE 06 – Rainwater harvesting	No rainwater harvesting	0.0	-0.7
W2_combined sewer	SE 13 – Flood risk management	No rainwater management (combined sewer)	0.0	-1.8
W3_permeable areas	SE 13 – Flood risk management	Rainwater management (permeable areas and drainage ditches)	1.8	0.0
L1_urban land	LE 02 – Land use	100% of the neighbourhood area is built on previously developed land	0.7	+0.7
L2_arable land	LE 02 – Land use	No credit for a development on arable land	0.0	0.0
L3_park	SE 11 – Green infrastructure	Public green infrastructure is provided within walking distance	1.8	+2.9
	LE 04 – Enhancement of ecological value	The park contributes to the enhancement of the ecological value	1.1	
T1_urban area	TM 04 – Access to public transport	The public transport stop is located at 50 m and the service frequency fulfils the requirements for urban areas	2.1	+0.5
T2_rural area	TM 04 – Access to public transport	The public transport stop is located at 1300 m and the service frequency fulfils the requirements for rural areas	0.5	-1.1
T3_bicycle path	TM 03 – Cycling network	Provision of bicycle paths	2.1	+2.1

Figure D.6: BREEAM scores for the reference new neighbourhood and the sustainability measures (Model 4_apartment).

Sustainaibility measures	Assessment issues	Description	Score (%)
Reference_new	MOB 01.01 – Proximity to daily destinations	The score for the proximity to daily destinations is 6.6 (all facilities at a distance between 1 and 2 km)	2.3
	MOB 02.01 – 'STOP' mobility principle	The neighbourhood has a good footpath infrastructure	1.8
	MOB 02.02 – Access to public transport	The neighbourhood fulfils the requirements for basic mobility for rural areas	1.0
		The score for the quality of public transport is 1.11 (local facilities at 10-20 min - regional facilities at 21-30 min)	
	FYS 01.01 – Location of the development	The neighbourhood is built on forest land (outside an existing residential area)	0.0
	FYS 02.01 – Urban heat island	The Urban Heat Island index of the neighbourhood is -1.38	1.2
	GRN 01.01 – Natural values	The green space factor of the original land use (forest land) and the neighbourhood are 2.5 and 0.79	0.0
	GRN 02.01 – Benefits of greenery	No collective green space - hedges delimiting the building lots	0.1
	WAT 02.01 – Water use	The total water consumption is 109 l/person.day - 24% of the total water consumption is covered by rainwater	0.4
	WAT 02.02 – Rain water management	Roof and paved areas are connected to an infiltration system (drainage ditches)	1.7
	WAT 02.03 – Waste water management	Wastewater gravity discharge to a separate sewer	0.3
	MAT 02.02 – Impact of materials in buildings	No material label (environmental declarations type I and III, labels for sustainable origin)	0.0
	MAT 02.01 – Impact of materials in the collective space	The external elements do not have the lowest LCA impact from all analysed variants	0.0
	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 54.8 kWh/m².year	0.0
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 162.7 kWh/m².year	0.0
		TOTAL	**8.8**

Figure D.7: DZM Wijken scores for the reference new neighbourhood (Model 1_detached).

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
M1_timber	MAT 02.02 – Impact of materials in buildings	No material label (environmental declarations type I and III, labels for sustainable origin)	0.0	0.0
M2_recycled materials	MAT 02.01 – Impact of materials in the collective space	The external elements have the lowest LCA impact from all analysed variants	2.1	+2.1
E1_non-insulated	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 321.1 kWh/m².year	0.0	0.0
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 489.2 kWh/m².year	0.0	
E2_passive standard	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 2.1 kWh/m².year	3.0	+3.0
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 97.1 kWh/m².year	0.0	
E3_oil boiler	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 160.9 kWh/m².year	0.0	0.0
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 308.3 kWh/m².year	0.0	
E4_heat pump	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 47.2 kWh/m².year	0.3	+0.3
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 80.1 kWh/m².year	0.0	
E5_no PV	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 103.2 kWh/m².year	0.0	0.0
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 206.9 kWh/m².year	0.0	
W1_no rainwater tank	WAT 02.01 – Water use	The total water consumption is 109 l/person.day - 0% of the total water consumption is covered by rainwater	0.0	-0.4
W2_combined sewer	WAT 02.02 – Rain water management	Roof and paved areas are connected to the combined sewer	0.0	-1.9
	WAT 02.03 – Waste water management	Wastewater discharge to a combined sewer	0.0	
W3_permeable areas	GRN 01.01 – Natural values	The green space factor of the original land use (forest land) and the neighbourhood are 2.5 and 0.83	0.5	+0.5
	WAT 02.02 – Rain water management	Permeable paved areas and roof areas connected to an infiltration system (drainage ditches)	1.7	
	WAT 02.03 – Waste water management	Wastewater gravity discharge to a sanitary sewer	0.3	
L1_urban land	FYS 01.01 – Location of the development	The neighbourhood is located on previously built urban land	3.8	+4.4
	GRN 01.01 – Natural values	The green space factor of the original land use (urban land) and the neighbourhood are identical (0.79)	0.5	
L2_arable land	FYS 01.01 – Location of the development	The neighbourhood is built on arable land (outside an existing residential area)	0.0	0.0
	GRN 01.01 – Natural values	The green space factor of the original land use (arable land) and the neighbourhood are 1 and 0.79 respectively	0.0	
L3_park	FYS 02.01 – Urban heat island	The Urban Heat Island index of the neighbourhood is -1.84	1.2	+1.0
	GRN 01.01 – Natural values	The green space factor of the original land use (forest land) and the neighbourhood are 2.5 and 0.85	0.5	
	GRN 02.01 – Benefits of greenery	A park of more than 1 ha is provided in the neighbourhood (maximum distance of 400 m from each dwelling)	0.6	
		The collective green space consists of 10.6 m²/inhabitant		
		The collective green space consists of 5.7% of the total neighbourhood area - hedges delimiting the building		
T1_urban area	MOB 01.01 – Proximity to daily destinations	The score for the proximity to daily destinations is 10 (most facilities at a distance lower than 500m)	3.5	+0.9
	MOB 02.02 – Access to public transport	The neighbourhood fulfils the requirements for basic mobility for urban areas	0.7	
		The score for the quality of public transport is 0.52 (most facilities within walking distance)		
T2_rural area	MOB 01.01 – Proximity to daily destinations	The score for the proximity to daily destinations is 6.1 (most facilities at a distance between 1 and 2 km)	2.3	-1.0
	MOB 02.02 – Access to public transport	The neighbourhood does not fulfil the requirements for basic mobility for rural areas (stop at 1300 m)	0.0	
T3_bicycle path	MOB 02.01 – 'STOP' mobility principle	The neighbourhood has a good footpath and cycling infrastructure	2.7	+0.9
	FYS 02.01 – Urban heat island	The Urban Heat Island index of the neighbourhood is -1.07	1.2	
	GRN 01.01 – Natural values	The green space factor of the original land use (forest land) and the neighbourhood are 2.5 and 0.74	0.0	

Figure D.8: DZM Wijken scores for the sustainability measures (Model 1_detached).

Sustainaibility measures	Assessment issues	Explanation	Score (%)
Reference_new	MOB 01.01 – Proximity to daily destinations	The score for the proximity to daily destinations is 6.6 (all facilities at a distance between 1 and 2 km)	2.3
	MOB 02.01 – 'STOP' mobility principle	The neighbourhood has a good footpath infrastructure	1.8
	MOB 02.02 – Access to public transport	The neighbourhood fulfils the requirements for basic mobility for rural areas	1.0
		The score for the quality of public transport is 1.11 (local facilities at 10-20 min - regional facilities at 21-30 min)	
	FYS 01.01 – Location of the development	The neighbourhood is built on forest land (outside an existing residential area)	0.0
	FYS 02.01 – Urban heat island	The Urban Heat Island index of the neighbourhood is -0.05	1.2
	GRN 01.01 – Natural values	The green space factor of the original land use (forest land) and the neighbourhood are 2.5 and 0.63	0.0
	GRN 02.01 – Benefits of greenery	No collective green space - hedges delimiting the building lots	0.1
	WAT 02.01 – Water use	The total water consumption is 109 l/person.day - 24% of the total water consumption is covered by rainwater	0.4
	WAT 02.02 – Rain water management	Roof and paved areas are connected to an infiltration system (drainage ditches)	1.7
	WAT 02.03 – Waste water management	Wastewater gravity discharge to a separate sewer	0.3
	MAT 02.02 – Impact of materials in buildings	No material label (environmental declarations type I and III, labels for sustainable origin)	0.0
	MAT 02.01 – Impact of materials in the collective space	The external elements do not have the lowest LCA impact from all analysed variants	0.0
	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 45.8 kWh/m².year	0.4
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 151 kWh/m².year	0.0
		TOTAL	**9.2**

Figure D.9: DZM Wijken scores for the reference new neighbourhood (Model 2_semidetached).

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
M1_timber	MAT 02.02 – Impact of materials in buildings	No material label (environmental declarations type I and III, labels for sustainable origin)	0.0	0.0
M2_recycled materials	MAT 02.01 – Impact of materials in the collective space	The external elements have the lowest LCA impact from all analysed variants	2.1	+2.1
E1_non-insulated	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 275.8 kWh/m².year	0.0	-0.4
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 433.2 kWh/m².year	0.0	
E2_passive standard	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is -1.5 kWh/m².year	3.0	+2.6
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 91.8 kWh/m².year	0.0	
E3_oil boiler	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 141.8 kWh/m².year	0.0	-0.4
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 282.6 kWh/m².year	0.0	
E4_heat pump	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 40.1 kWh/m².year	1.0	+0.6
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 76.6 kWh/m².year	0.0	
E5_no PV	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 94.2 kWh/m².year	0.0	-0.4
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 195.1 kWh/m².year	0.0	
W1_no rainwater tank	WAT 02.01 – Water use	The total water consumption is 109 l/person.day - 0% of the total water consumption is covered by rainwater	0.0	-0.4
W2_combined sewer	WAT 02.02 – Rain water management	Roof and paved areas are connected to the combined sewer	0.0	-1.9
	WAT 02.03 – Waste water management	Wastewater discharge to a combined sewer	0.0	
W3_permeable areas	GRN 01.01 – Natural values	The green space factor of the original land use (forest land) and the neighbourhood are 2.5 and 0.69	0.0	0.0
	WAT 02.02 – Rain water management	Permeable paved areas and roof areas connected to an infiltration system (drainage ditches)	1.7	
	WAT 02.03 – Waste water management	Wastewater gravity discharge to a sanitary sewer	0.3	
L1_urban land	FYS 01.01 – Location of the development	The neighbourhood is located on previously built urban land	3.8	+4.4
	GRN 01.01 – Natural values	The green space factor of the original land use (urban land) and the neighbourhood are identical (0.63)	0.5	
L2_arable land	FYS 01.01 – Location of the development	The neighbourhood is built on arable land (outside an existing residential area)	0.0	0.0
	GRN 01.01 – Natural values	The green space factor of the original land use (arable land) and the neighbourhood are 1 and 0.63 respectively	0.0	
L3_park	FYS 02.01 – Urban heat island	The Urban Heat Island index of the neighbourhood is -0.82	1.2	+0.5
	GRN 01.01 – Natural values	The green space factor of the original land use (forest land) and the neighbourhood are 2.5 and 0.73	0.0	
	GRN 02.01 – Benefits of greenery	A park of more than 1 ha is provided in the neighbourhood (maximum distance of 400 m from each dwelling)	0.6	
		The collective green space consists of 10.6 m²/inhabitant		
		The collective green space consists of 9.7% of the total neighbourhood area - hedges delimiting the building		
T1_urban area	MOB 01.01 – Proximity to daily destinations	The score for the proximity to daily destinations is 10 (most facilities at a distance lower than 500m)	3.5	+0.9
	MOB 02.02 – Access to public transport	The neighbourhood fulfils the requirements for basic mobility for urban areas	0.7	
		The score for the quality of public transport is 0.52 (most facilities within walking distance)		
T2_rural area	MOB 01.01 – Proximity to daily destinations	The score for the proximity to daily destinations is 6.1 (most facilities at a distance between 1 and 2 km)	2.3	-1.0
	MOB 02.02 – Access to public transport	The neighbourhood does not fulfil the requirements for basic mobility for rural areas (stop at 1300 m)	0.0	
T3_bicycle path	MOB 02.01 – 'STOP' mobility principle	The neighbourhood has a good footpath and cycling infrastructure	2.7	+0.6
	FYS 02.01 – Urban heat island	The Urban Heat Island index of the neighbourhood is 0.25	0.9	
	GRN 01.01 – Natural values	The green space factor of the original land use (forest land) and the neighbourhood are 2.5 and 0.58	0.0	

Figure D.10: DZM Wijken scores for the sustainability measures (Model 2_semidetached).

Sustainaibility measures	Assessment issues	Explanation	Score (%)
Reference_new	MOB 01.01 – Proximity to daily destinations	The score for the proximity to daily destinations is 6.6 (all facilities at a distance between 1 and 2 km)	2.3
	MOB 02.01 – 'STOP' mobility principle	The neighbourhood has a good footpath infrastructure	1.8
	MOB 02.02 – Access to public transport	The neighbourhood fulfils the requirements for basic mobility for rural areas	1.0
		The score for the quality of public transport is 1.11 (local facilities at 10-20 min - regional facilities at 21-30 min)	
	FYS 01.01 – Location of the development	The neighbourhood is built on forest land (outside an existing residential area)	0.0
	FYS 02.01 – Urban heat island	The Urban Heat Island index of the neighbourhood is 0.94	0.0
	GRN 01.01 – Natural values	The green space factor of the original land use (forest land) and the neighbourhood are 2.5 and 0.53	0.0
	GRN 02.01 – Benefits of greenery	No collective green space - hedges delimiting the building lots	0.1
	WAT 02.01 – Water use	The total water consumption is 109 l/person.day - 24% of the total water consumption is covered by rainwater	0.4
	WAT 02.02 – Rain water management	Roof and paved areas are connected to an infiltration system (drainage ditches)	1.7
	WAT 02.03 – Waste water management	Wastewater gravity discharge to a separate sewer	0.3
	MAT 02.02 – Impact of materials in buildings	No material label (environmental declarations type I and III, labels for sustainable origin)	0.0
	MAT 02.01 – Impact of materials in the collective space	The external elements do not have the lowest LCA impact from all analysed variants	0.0
	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 33.9 kWh/m².year	1.6
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 135.5 kWh/m².year	0.0
		TOTAL	**9.2**

Figure D.11: DZM Wijken scores for the reference new neighbourhood (Model 3_terraced).

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
M1_timber	MAT 02.02 – Impact of materials in buildings	No material label (environmental declarations type I and III, labels for sustainable origin)	0.0	0.0
M2_recycled materials	MAT 02.01 – Impact of materials in the collective space	The external elements have the lowest LCA impact from all analysed variants	2.1	+2.1
E1_non-insulated	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 221 kWh/m².year	0.0	-1.6
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 365.3 kWh/m².year	0.0	
E2_passive standard	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is -5.8 kWh/m².year	3.0	+1.4
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 85.6 kWh/m².year	0.0	
E3_oil boiler	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 116.5 kWh/m².year	0.0	-1.6
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 248.7 kWh/m².year	0.0	
E4_heat pump	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 30.7 kWh/m².year	1.9	+0.3
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 72 kWh/m².year	0.0	
E5_no PV	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 82.4 kWh/m².year	0.0	-1.6
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 179.6 kWh/m².year	0.0	
W1_no rainwater tank	WAT 02.01 – Water use	The total water consumption is 109 l/person.day - 0% of the total water consumption is covered by rainwater	0.0	-0.4
W2_combined sewer	WAT 02.02 – Rain water management	Roof and paved areas are connected to the combined sewer	0.0	-1.9
	WAT 02.03 – Waste water management	Wastewater discharge to a combined sewer	0.0	
W3_permeable areas	GRN 01.01 – Natural values	The green space factor of the original land use (forest land) and the neighbourhood are 2.5 and 0.6 respectively	0.0	0.0
	WAT 02.02 – Rain water management	Permeable paved areas and roof areas connected to an infiltration system (drainage ditches)	1.7	
	WAT 02.03 – Waste water management	Wastewater gravity discharge to a sanitary sewer	0.3	
L1_urban land	FYS 01.01 – Location of the development	The neighbourhood is located on previously built urban land	3.8	+4.4
	GRN 01.01 – Natural values	The green space factor of the original land use (urban land) and the neighbourhood are identical (0.53)	0.5	
L2_arable land	FYS 01.01 – Location of the development	The neighbourhood is built on arable land (outside an existing residential area)	0.0	0.0
	GRN 01.01 – Natural values	The green space factor of the original land use (arable land) and the neighbourhood are 1 and 0.53 respectively	0.0	
L3_park	FYS 02.01 – Urban heat island	The Urban Heat Island index of the neighbourhood is -0.23	1.2	+1.9
	GRN 01.01 – Natural values	The green space factor of the original land use (forest land) and the neighbourhood are 2.5 and 0.69	0.0	
	GRN 02.01 – Benefits of greenery	A park of more than 1 ha is provided in the neighbourhood (maximum distance of 400 m from each dwelling)	0.8	
		The collective green space consists of 10.6 m²/inhabitant		
		The collective green space consists of 14.6% of the total neighbourhood area - hedges delimiting the building		
T1_urban area	MOB 01.01 – Proximity to daily destinations	The score for the proximity to daily destinations is 10 (most facilities at a distance lower than 500m)	3.5	+0.9
	MOB 02.02 – Access to public transport	The neighbourhood fulfils the requirements for basic mobility for urban areas	0.7	
		The score for the quality of public transport is 0.52 (most facilities within walking distance)		
T2_rural area	MOB 01.01 – Proximity to daily destinations	The score for the proximity to daily destinations is 6.1 (most facilities at a distance between 1 and 2 km)	2.3	-1.0
	MOB 02.02 – Access to public transport	The neighbourhood does not fulfil the requirements for basic mobility for rural areas (stop at 1300 m)	0.0	
T3_bicycle path	MOB 02.01 – 'STOP' mobility principle	The neighbourhood has a good footpath and cycling infrastructure	2.7	+0.9
	FYS 02.01 – Urban heat island	The Urban Heat Island index of the neighbourhood is 1.14	0.0	
	GRN 01.01 – Natural values	The green space factor of the original land use (forest land) and the neighbourhood are 2.5 and 0.5 respectively	0.0	

Figure D.12: DZM Wijken scores for the sustainability measures (Model 3_terraced).

Sustainaibility measures	Assessment issues	Explanation	Score (%)
Reference_new	MOB 01.01 – Proximity to daily destinations	The score for the proximity to daily destinations is 6.6 (all facilities at a distance between 1 and 2 km)	2.3
	MOB 02.01 – 'STOP' mobility principle	The neighbourhood has a good footpath infrastructure	1.8
	MOB 02.02 – Access to public transport	The neighbourhood fulfils the requirements for basic mobility for rural areas	1.0
		The score for the quality of public transport is 1.11 (local facilities at 10-20 min - regional facilities at 21-30 min)	
	FYS 01.01 – Location of the development	The neighbourhood is built on forest land (outside an existing residential area)	0.0
	FYS 02.01 – Urban heat island	The Urban Heat Island index of the neighbourhood is 1.9	0.0
	GRN 01.01 – Natural values	The green space factor of the original land use (forest land) and the neighbourhood are 2.5 and 0.28	0.0
	GRN 02.01 – Benefits of greenery	The collective green space consists of 9.4 m²/inhabitant	0.4
		The collective green space consists of 26.2% of the total neighbourhood area - hedges delimiting the building	
	WAT 02.01 – Water use	The total water consumption is 109 l/person.day - 7% of the total water consumption is covered by rainwater	0.0
	WAT 02.02 – Rain water management	Roof and paved areas are connected to an infiltration system (drainage ditches)	1.7
	WAT 02.03 – Waste water management	Wastewater gravity discharge to a separate sewer	0.3
	MAT 02.02 – Impact of materials in buildings	No material label (environmental declarations type I and III, labels for sustainable origin)	0.0
	MAT 02.01 – Impact of materials in the collective space	The external elements do not have the lowest LCA impact from all analysed variants	0.0
	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 48.9 kWh/m².year	0.1
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 162.7 kWh/m².year	0.0
		TOTAL	**7.5**

Figure D.13: DZM Wijken scores for the reference new neighbourhood (Model 4_apartment).

Sustainability measures	Assessment issues	Description	Score (%)	Δ REF (%)
M1_timber	MAT 02.02 – Impact of materials in buildings	No material label (environmental declarations type I and III, labels for sustainable origin)	0.0	0.0
M2_recycled materials	MAT 02.01 – Impact of materials in the collective space	The external elements have the lowest LCA impact from all analysed variants	2.1	+2.1
E1_non-insulated	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 131.1 kWh/m².year	0.0	-0.1
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 246.1 kWh/m².year	0.0	
E2_passive standard	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 19.3 kWh/m².year	3.0	+2.9
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 106.6 kWh/m².year	0.0	
E3_oil boiler	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 116.3 kWh/m².year	0.0	-0.1
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 236.7 kWh/m².year	0.0	
E4_heat pump	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 48.4 kWh/m².year	0.2	+0.0
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 92.8 kWh/m².year	0.0	
E5_no PV	ENE B.01.01 – Reduction of net energy demand	The primary building related neighbourhood energy demand is 69 kWh/m².year	0.0	-0.1
	ENE B.01.03 – Non-renewable primary final energy use	The non-renewable primary final energy use of the neighbourhood is 162.5 kWh/m².year	0.0	
W1_no rainwater tank	WAT 02.01 – Water use	The total water consumption is 109 l/person.day - 0% of the total water consumption is covered by rainwater	0.0	0.0
W2_combined sewer	WAT 02.02 – Rain water management	Roof and paved areas are connected to the combined sewer	0.0	-1.9
	WAT 02.03 – Waste water management	Wastewater discharge to a combined sewer	0.0	
W3_permeable areas	GRN 01.01 – Natural values	The green space factor of the original land use (forest land) and the neighbourhood are 2.5 and 0.4 respectively	0.0	0.0
	WAT 02.02 – Rain water management	Permeable paved areas and roof areas connected to an infiltration system (drainage ditches)	1.7	
	WAT 02.03 – Waste water management	Wastewater gravity discharge to a sanitary sewer	0.3	
L1_urban land	FYS 01.01 – Location of the development	The neighbourhood is located on previously built urban land	3.8	+4.4
	GRN 01.01 – Natural values	The green space factor of the original land use (urban land) and the neighbourhood are identical (0.28)	0.5	
L2_arable land	FYS 01.01 – Location of the development	The neighbourhood is built on arable land (outside an existing residential area)	0.0	0.0
	GRN 01.01 – Natural values	The green space factor of the original land use (arable land) and the neighbourhood are 1 and 0.28 respectively	0.0	
L3_park	FYS 02.01 – Urban heat island	The Urban Heat Island index of the neighbourhood is -0.47	1.2	+1.9
	GRN 01.01 – Natural values	The green space factor of the original land use (forest land) and the neighbourhood are 2.5 and 0.6 respectively	0.0	
	GRN 02.01 – Benefits of greenery	A park of more than 1 ha is provided in the neighbourhood (maximum distance of 400 m from each dwelling)	1.1	
		The collective green space consists of 20 m²/inhabitant		
		The collective green space consists of 55.9% of the total neighbourhood area - hedges delimiting the building		
T1_urban area	MOB 01.01 – Proximity to daily destinations	The score for the proximity to daily destinations is 10 (most facilities at a distance lower than 500m)	3.5	+0.9
	MOB 02.02 – Access to public transport	The neighbourhood fulfils the requirements for basic mobility for urban areas	0.7	
		The score for the quality of public transport is 0.52 (most facilities within walking distance)		
T2_rural area	MOB 01.01 – Proximity to daily destinations	The score for the proximity to daily destinations is 6.1 (most facilities at a distance between 1 and 2 km)	2.3	-1.0
	MOB 02.02 – Access to public transport	The neighbourhood does not fulfil the requirements for basic mobility for rural areas (stop at 1300 m)	0.0	
T3_bicycle path	MOB 02.01 – 'STOP' mobility principle	The neighbourhood has a good footpath and cycling infrastructure	2.7	+0.9
	FYS 02.01 – Urban heat island	The Urban Heat Island index of the neighbourhood is 2.01	0.0	
	GRN 01.01 – Natural values	The green space factor of the original land use (forest land) and the neighbourhood are 2.5 and 0.27	0.0	

Figure D.14: DZM Wijken scores for the sustainability measures (Model 4_apartment).

Sustainaibility measures	Assessment issues	Description	Score (%)
Reference_new	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3
	ENV1.2 – Water and soil protection	The percentage of sealed areas is 33%	0.6
	ENV1.3 – Change in urban climate	The urban climate index is 1.18	0.5
	ENV1.4 – Biodiversity and integration	The biotope area factor is 0.4	0.2
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4
	ENV2.3 – Energy efficient building structure	The building compactness is 0.8	0.7
		The percentage of solar oriented living areas is 100% and the factor for the active use of solar energy is 35%	
	ENV2.4 – Resource saving infrastructure	No reclaimed or recycled material in the public realm	0.0
	ENV2.6 – Water cycle system	Drinking water use of 2.2 l/m².day - reuse of rainwater in buildings - local infiltration - separated sewer	0.9
	ECO1.1 – Life cycle costing	Based on LCC results for the buildings and public spaces	4.9
	ECO2.2 – Space efficiency	The built density index is 1.22	1.7
	SOC1.2 – Social and profit oriented infrastructure	The score for the access to social and profit oriented infrastructure is assumed to be 50 (reference value)	0.9
	SOC2.2 – Sojourn quality in public spaces	No greenery in the public space (square) - good solar access - no summer shading by trees	0.0
	SOC3.1 – Open space supply	Public open space of 0.28 m²/m² UFA - private open space of 3.36 m²/m² UFA	2.0
	SOC3.2 – Accessibility	The score for the access to essential infrastructure is assumed to be 15 (reference value)	0.3
	TEC1.1 – Energy technique	The primary energy factor for space heating is 1	0.5
	TEC1.3 – Rain water management	Reuse of rainwater in buildings - rainwater infiltration - only emergency overflow connected to surface water	0.6
	TEC3.1 – Quality of traffic system	Station at less than 20 min - 1 bus line - frequency of 1 bus per hour - no bicycle path - footpaths	0.5
	TEC3.3 – Quality of public transport infrastructure	The public transport stop is located at 750 m - no intermodal platform at 350 m	0.0
	TEC3.4 – Quality of cycling infrastructure	No cycling infrastructure	0.0
		TOTAL	**17.1**

* GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, AP = Acidification Potential, EP = Eutrophication Potential

Figure D.15: DGNB scores for the reference new neighbourhood (Model 1_detached).

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
M1_timber	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.2	-0.1
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.9	
M2_recycled materials	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	-2.3
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ENV2.4 – Resource saving infrastructure	More than 10% of the mass of materials used in the public realm is reclaimed and more than 60% is recycled	0.4	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	2.3	
E1_non-insulated	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	0.3	-2.2
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	0.7	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.4	
E2_passive standard	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.6	+0.8
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.8	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	5.0	
E3_oil boiler	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	0.9	-1.2
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	0.8	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.7	
E4_heat pump	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.2	-0.5
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.5	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.9	
	TEC1.1 – Energy technique	The primary energy factor for space heating is 2.5	0.0	
E5_no PV	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.0	-0.4
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.2	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.9	

* GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, AP = Acidification Potential, EP = Eutrophication Potential

Figure D.16: DGNB scores for the sustainability measures related to material use and operational energy use (Model 1_detached).

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
W1_no rainwater tank	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	-0.6
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ENV2.6 – Water cycle system	Drinking water use of 2.9 l/m².day - no reuse of rainwater - local infiltration - separated sewer	0.5	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.9	
	TEC1.3 – Rain water management	No reuse of rainwater - rainwater infiltration - only emergency overflow connected to surface water	0.4	
W2_combined sewer	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	-0.9
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ENV2.6 – Water cycle system	Drinking water use of 2.2 l/m².day - reuse of rainwater in buildings - no infiltration - combined sewer	0.4	
	TEC1.3 – Rain water management	Reuse of rainwater in buildings - no infiltration - combined sewer	0.2	
W3_permeable areas	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	-0.0
	ENV1.2 – Water and soil protection	The percentage of sealed areas is 21%	0.7	
	ENV1.4 – Biodiversity and integration	The biotope area factor is 0.45	0.2	
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ENV2.6 – Water cycle system	Drinking water use of 2.2 l/m².day - reuse of rainwater in buildings - permeable materials and infiltration -	0.9	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.6	
	TEC1.3 – Rain water management	Permeable paved areas - reuse of rainwater in buildings - rainwater infiltration - no connection to surface water	0.8	
L1_urban land	-	No credit for a development on urban land	0.0	0.0
L2_arable land	-	No credit for a development on arable land	0.0	0.0
L3_park	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	+0.9
	ENV1.2 – Water and soil protection	The percentage of sealed areas is 27%	0.7	
	ENV1.3 – Change in urban climate	The urban climate index is 1.29	0.7	
	ENV1.4 – Biodiversity and integration	The biotope area factor is 0.5	0.3	
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	5.5	
	SOC2.2 – Sojourn quality in public spaces	More than 80% of the public space area is green (park) - good solar access - summer shading by trees	0.1	

* GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, AP = Acidification Potential, EP = Eutrophication Potential

Figure D.17: DGNB scores for the sustainability measures related to operational water use and primary land use (Model 1_detached).

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
T1_urban area	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.8	+2.9
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.5	
	SOC1.2 – Social and profit oriented infrastructure	The score for the access to social and profit oriented infrastructure is 100	1.8	
	SOC3.2 – Accessibility	The score for the access to essential infrastructure is 30	0.5	
	TEC3.1 – Quality of traffic system	Station at less than 5 min - 2 bus lines - frequency of 4 buses per hour - no bicycle path - footpaths	0.7	
	TEC3.3 – Quality of public transport infrastructure	The public transport stop is located at 50 m - intermodal platform (train/bus) at 350 m	0.8	
T2_rural area	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.1	-0.9
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.2	
	SOC1.2 – Social and profit oriented infrastructure	The score for the access to social and profit oriented infrastructure is 38	0.7	
	SOC3.2 – Accessibility	The score for the access to essential infrastructure is 0	0.0	
	TEC3.1 – Quality of traffic system	Station at less than 25 min - 1 bus line - frequency of 1 bus per hour - no bicycle path - footpaths	0.5	
	TEC3.3 – Quality of public transport infrastructure	The public transport stop is located at 1300 m - no intermodal platform at 350 m	0.0	
T3_bicycle path	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.5	+0.3
	ENV1.2 – Water and soil protection	The percentage of sealed areas is 37%	0.6	
	ENV1.3 – Change in urban climate	The urban climate index is 1.11	0.5	
	ENV1.4 – Biodiversity and integration	The biotope area factor is 0.38	0.2	
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.5	
	ENV2.3 – Energy efficient building structure	The building compactness is 0.8	0.7	
		The percentage of solar oriented living areas is 100% and the factor for the active use of solar energy is 35%		
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.2	
	ECO2.2 – Space efficiency	The built density index is 1.00	1.4	
	TEC3.1 – Quality of traffic system	Station at less than 20 min - 1 bus line - frequency of 1 bus per hour - bicycle paths - footpaths	0.8	
	TEC3.4 – Quality of cycling infrastructure	Qualitative cycling infrastructure	0.8	

* GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, AP = Acidification Potential, EP = Eutrophication Potential

Figure D.18: DGNB scores for the sustainability measures related to user transport (Model 1_detached).

Sustainaibility measures	Assessment issues	Description	Score (%)
Reference_new	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3
	ENV1.2 – Water and soil protection	The percentage of sealed areas is 49%	0.6
	ENV1.3 – Change in urban climate	The urban climate index is 1.05	0.5
	ENV1.4 – Biodiversity and integration	The biotope area factor is 0.3	0.2
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4
	ENV2.3 – Energy efficient building structure	The building compactness is 0.67	0.9
		The percentage of solar oriented living areas is 100% and the factor for the active use of solar energy is 35%	
	ENV2.4 – Resource saving infrastructure	No reclaimed or recycled material in the public realm	0.0
	ENV2.6 – Water cycle system	Drinking water use of 2.2 l/m².day - reuse of rainwater in buildings - local infiltration - separated sewer	0.9
	ECO1.1 – Life cycle costing	Based on LCC results for the buildings and public spaces	4.9
	ECO2.2 – Space efficiency	The built density index is 1.66	2.3
	SOC1.2 – Social and profit oriented infrastructure	The score for the access to social and profit oriented infrastructure is assumed to be 50 (reference value)	0.9
	SOC2.2 – Sojourn quality in public spaces	No greenery in the public space (square) - good solar access - no summer shading by trees	0.0
	SOC3.1 – Open space supply	Public open space of 0.28 m²/m² UFA - private open space of 1.48 m²/m² UFA	2.0
	SOC3.2 – Accessibility	The score for the access to essential infrastructure is assumed to be 15 (reference value)	0.3
	TEC1.1 – Energy technique	The primary energy factor for space heating is 1	0.5
	TEC1.3 – Rain water management	Reuse of rainwater in buildings - rainwater infiltration - only emergency overflow connected to surface water	0.6
	TEC3.1 – Quality of traffic system	Station at less than 20 min - 1 bus line - frequency of 1 bus per hour - no bicycle path - footpaths	0.5
	TEC3.3 – Quality of public transport infrastructure	The public transport stop is located at 750 m - no intermodal platform at 350 m	0.0
	TEC3.4 – Quality of cycling infrastructure	No cycling infrastructure	0.0
		TOTAL	**17.7**

* GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, AP = Acidification Potential, EP = Eutrophication Potential

Figure D.19: DGNB scores for the reference new neighbourhood (Model 2_semidetached).

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
M1_timber	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.2	-0.0
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.5	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.8	
M2_recycled materials	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	-2.4
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ENV2.4 – Resource saving infrastructure	More than 10% of the mass of materials used in the public realm is reclaimed and more than 60% is recycled	0.4	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	2.1	
E1_non-insulated	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	0.5	-2.1
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	0.7	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.3	
E2_passive standard	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.6	+0.7
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.6	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.9	
E3_oil boiler	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	0.9	-1.2
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	0.9	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.5	
E4_heat pump	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.2	-0.5
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.5	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.9	
	TEC1.1 – Energy technique	The primary energy factor for space heating is 2.5	0.0	
E5_no PV	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.0	-0.6
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.1	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.8	

* GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, AP = Acidification Potential, EP = Eutrophication Potential

Figure D.20: DGNB scores for the sustainability measures related to material use and operational energy use (Model 2_semidetached).

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
W1_no rainwater tank	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	-0.6
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ENV2.6 – Water cycle system	Drinking water use of 2.9 l/m².day - no reuse of rainwater - local infiltration - separated sewer	0.5	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.9	
	TEC1.3 – Rain water management	No reuse of rainwater - rainwater infiltration - only emergency overflow connected to surface water	0.4	
W2_combined sewer	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	-0.9
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ENV2.6 – Water cycle system	Drinking water use of 2.2 l/m².day - reuse of rainwater in buildings - no infiltration - combined sewer	0.4	
	TEC1.3 – Rain water management	Reuse of rainwater in buildings - no infiltration - combined sewer	0.2	
W3_permeable areas	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	-0.0
	ENV1.2 – Water and soil protection	The percentage of sealed areas is 33%	0.6	
	ENV1.4 – Biodiversity and integration	The biotope area factor is 0.37	0.2	
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ENV2.6 – Water cycle system	Drinking water use of 2.2 l/m².day - reuse of rainwater in buildings - permeable materials and infiltration -	0.9	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.5	
	TEC1.3 – Rain water management	Permeable paved areas - reuse of rainwater in buildings - rainwater infiltration - no connection to surface water	0.8	
L1_urban land	-	No credit for a development on urban land	0.0	0.0
L2_arable land	-	No credit for a development on arable land	0.0	0.0
L3_park	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	+1.1
	ENV1.2 – Water and soil protection	The percentage of sealed areas is 40%	0.6	
	ENV1.3 – Change in urban climate	The urban climate index is 1.24	0.7	
	ENV1.4 – Biodiversity and integration	The biotope area factor is 0.46	0.2	
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	5.6	
	SOC2.2 – Sojourn quality in public spaces	More than 80% of the public space area is green (park) - good solar access - summer shading by trees	0.1	

* GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, AP = Acidification Potential, EP = Eutrophication Potential

Figure D.21: DGNB scores for the sustainability measures related to operational water use and primary land use (Model 2_semidetached).

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
T1_urban area	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.8	+3.0
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.6	
	SOC1.2 – Social and profit oriented infrastructure	The score for the access to social and profit oriented infrastructure is 100	1.8	
	SOC3.2 – Accessibility	The score for the access to essential infrastructure is 30	0.5	
	TEC3.1 – Quality of traffic system	Station at less than 5 min - 2 bus lines - frequency of 4 buses per hour - no bicycle path - footpaths	0.7	
	TEC3.3 – Quality of public transport infrastructure	The public transport stop is located at 50 m - intermodal platform (train/bus) at 350 m	0.8	
T2_rural area	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.1	-0.9
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.2	
	SOC1.2 – Social and profit oriented infrastructure	The score for the access to social and profit oriented infrastructure is 38	0.7	
	SOC3.2 – Accessibility	The score for the access to essential infrastructure is 0	0.0	
	TEC3.1 – Quality of traffic system	Station at less than 25 min - 1 bus line - frequency of 1 bus per hour - no bicycle path - footpaths	0.5	
	TEC3.3 – Quality of public transport infrastructure	The public transport stop is located at 1300 m - no intermodal platform at 350 m	0.0	
T3_bicycle path	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.5	+0.2
	ENV1.2 – Water and soil protection	The percentage of sealed areas is 53%	0.6	
	ENV1.3 – Change in urban climate	The urban climate index is 0.97	0.4	
	ENV1.4 – Biodiversity and integration	The biotope area factor is 0.28	0.2	
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.5	
	ENV2.3 – Energy efficient building structure	The building compactness is 0.67	0.9	
		The percentage of solar oriented living areas is 100% and the factor for the active use of solar energy is 35%		
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.2	
	ECO2.2 – Space efficiency	The built density index is 1.41	1.9	
	TEC3.1 – Quality of traffic system	Station at less than 20 min - 1 bus line - frequency of 1 bus per hour - bicycle paths - footpaths	0.8	
	TEC3.4 – Quality of cycling infrastructure	Qualitative cycling infrastructure	0.8	

* GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, AP = Acidification Potential, EP = Eutrophication Potential

Figure D.22: DGNB scores for the sustainability measures related to user transport (Model 2_semidetached).

Sustainaibility measures	Assessment issues	Description	Score (%)
Reference_new	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3
	ENV1.2 – Water and soil protection	The percentage of sealed areas is 62%	0.5
	ENV1.3 – Change in urban climate	The urban climate index is 0.94	0.4
	ENV1.4 – Biodiversity and integration	The biotope area factor is 0.23	0.1
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4
	ENV2.3 – Energy efficient building structure	The building compactness is 0.51	1.0
		The percentage of solar oriented living areas is 100% and the factor for the active use of solar energy is 35%	
	ENV2.4 – Resource saving infrastructure	No reclaimed or recycled material in the public realm	0.0
	ENV2.6 – Water cycle system	Drinking water use of 2.2 l/m².day - reuse of rainwater in buildings - local infiltration - separated sewer	0.9
	ECO1.1 – Life cycle costing	Based on LCC results for the buildings and public spaces	5.2
	ECO2.2 – Space efficiency	The built density index is 2.25	3.1
	SOC1.2 – Social and profit oriented infrastructure	The score for the access to social and profit oriented infrastructure is assumed to be 50 (reference value)	0.9
	SOC2.2 – Sojourn quality in public spaces	No greenery in the public space (square) - good solar access - no summer shading by trees	0.0
	SOC3.1 – Open space supply	Public open space of 0.28 m²/m² UFA - private open space of 0.74 m²/m² UFA	2.0
	SOC3.2 – Accessibility	The score for the access to essential infrastructure is assumed to be 15 (reference value)	0.3
	TEC1.1 – Energy technique	The primary energy factor for space heating is 1	0.5
	TEC1.3 – Rain water management	Reuse of rainwater in buildings - rainwater infiltration - only emergency overflow connected to surface water	0.6
	TEC3.1 – Quality of traffic system	Station at less than 20 min - 1 bus line - frequency of 1 bus per hour - no bicycle path - footpaths	0.5
	TEC3.3 – Quality of public transport infrastructure	The public transport stop is located at 750 m - no intermodal platform at 350 m	0.0
	TEC3.4 – Quality of cycling infrastructure	No cycling infrastructure	0.0
		TOTAL	**18.7**

* GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, AP = Acidification Potential, EP = Eutrophication Potential

Figure D.23: DGNB scores for the reference new neighbourhood (Model 3_terraced).

Sustainability measures	Assessment issues	Description	Score (%)	Δ REF (%)
M1_timber	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.2	-0.1
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.5	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	5.1	
M2_recycled materials	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.4	-2.2
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ENV2.4 – Resource saving infrastructure	More than 10% of the mass of materials used in the public realm is reclaimed and more than 60% is recycled	0.4	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	2.6	
E1_non-insulated	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	0.6	-2.1
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	0.7	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.4	
E2_passive standard	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.6	+0.6
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.6	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	5.3	
E3_oil boiler	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	0.9	-1.3
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	0.9	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.7	
E4_heat pump	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.2	-0.5
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.5	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	5.2	
	TEC1.1 – Energy technique	The primary energy factor for space heating is 2.5	0.0	
E5_no PV	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.0	-0.6
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.1	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	5.1	

* GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, AP = Acidification Potential, EP = Eutrophication Potential

Figure D.24: DGNB scores for the sustainability measures related to material use and operational energy use (Model 3_terraced).

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
W1_no rainwater tank	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	-0.6
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ENV2.6 – Water cycle system	Drinking water use of 2.9 l/m².day - no reuse of rainwater - local infiltration - separated sewer	0.5	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	5.2	
	TEC1.3 – Rain water management	No reuse of rainwater - rainwater infiltration - only emergency overflow connected to surface water	0.4	
W2_combined sewer	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	-0.9
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ENV2.6 – Water cycle system	Drinking water use of 2.2 l/m².day - reuse of rainwater in buildings - no infiltration - combined sewer	0.4	
	TEC1.3 – Rain water management	Reuse of rainwater in buildings - no infiltration - combined sewer	0.2	
W3_permeable areas	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	-0.1
	ENV1.2 – Water and soil protection	The percentage of sealed areas is 44%	0.6	
	ENV1.4 – Biodiversity and integration	The biotope area factor is 0.30	0.2	
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ENV2.6 – Water cycle system	Drinking water use of 2.2 l/m².day - reuse of rainwater in buildings - permeable materials and infiltration -	0.9	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.8	
	TEC1.3 – Rain water management	Permeable paved areas - reuse of rainwater in buildings - rainwater infiltration - no connection to surface water	0.8	
L1_urban land	-	No credit for a development on urban land	0.0	0.0
L2_arable land	-	No credit for a development on arable land	0.0	0.0
L3_park	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	+1.5
	ENV1.2 – Water and soil protection	The percentage of sealed areas is 47%	0.6	
	ENV1.3 – Change in urban climate	The urban climate index is 1.23	0.7	
	ENV1.4 – Biodiversity and integration	The biotope area factor is 0.47	0.3	
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	6.1	
	SOC2.2 – Sojourn quality in public spaces	More than 80% of the public space area is green (park) - good solar access - summer shading by trees	0.1	

* GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, AP = Acidification Potential, EP = Eutrophication Potential

Figure D.25: DGNB scores for the sustainability measures related to operational water use and primary land use (Model 3_terraced).

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
T1_urban area	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.8	+3.0
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.6	
	SOC1.2 – Social and profit oriented infrastructure	The score for the access to social and profit oriented infrastructure is 100	1.8	
	SOC3.2 – Accessibility	The score for the access to essential infrastructure is 30	0.5	
	TEC3.1 – Quality of traffic system	Station at less than 5 min - 2 bus lines - frequency of 4 buses per hour - no bicycle path - footpaths	0.7	
	TEC3.3 – Quality of public transport infrastructure	The public transport stop is located at 50 m - intermodal platform (train/bus) at 350 m	0.8	
T2_rural area	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.1	-0.9
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.2	
	SOC1.2 – Social and profit oriented infrastructure	The score for the access to social and profit oriented infrastructure is 38	0.7	
	SOC3.2 – Accessibility	The score for the access to essential infrastructure is 0	0.0	
	TEC3.1 – Quality of traffic system	Station at less than 25 min - 1 bus line - frequency of 1 bus per hour - no bicycle path - footpaths	0.5	
	TEC3.3 – Quality of public transport infrastructure	The public transport stop is located at 1300 m - no intermodal platform at 350 m	0.0	
T3_bicycle path	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.6	+0.6
	ENV1.2 – Water and soil protection	The percentage of sealed areas is 64%	0.5	
	ENV1.3 – Change in urban climate	The urban climate index is 0.87	0.4	
	ENV1.4 – Biodiversity and integration	The biotope area factor is 0.21	0.1	
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.5	
	ENV2.3 – Energy efficient building structure	The building compactness is 0.51	1.0	
		The percentage of solar oriented living areas is 100% and the factor for the active use of solar energy is 35%		
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.7	
	ECO2.2 – Space efficiency	The built density index is 2.01	2.7	
	TEC3.1 – Quality of traffic system	Station at less than 20 min - 1 bus line - frequency of 1 bus per hour - bicycle paths - footpaths	0.8	
	TEC3.4 – Quality of cycling infrastructure	Qualitative cycling infrastructure	0.8	

* GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, AP = Acidification Potential, EP = Eutrophication Potential

Figure D.26: DGNB scores for the sustainability measures related to user transport (Model 3_terraced).

Sustainaibility measures	Assessment issues	Description	Score (%)
Reference_new	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3
	ENV1.2 – Water and soil protection	The percentage of sealed areas is 74%	0.5
	ENV1.3 – Change in urban climate	The urban climate index is 0.54	0.0
	ENV1.4 – Biodiversity and integration	The biotope area factor is 0.16	0.1
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4
	ENV2.3 – Energy efficient building structure	The building compactness is 0.25	1.2
		The percentage of solar oriented living areas is 87.5% and the factor for the active use of solar energy is 35%	
	ENV2.4 – Resource saving infrastructure	No reclaimed or recycled material in the public realm	0.0
	ENV2.6 – Water cycle system	Drinking water use of 2.7 l/m².day - reuse of rainwater in buildings - local infiltration - separated sewer	0.7
	ECO1.1 – Life cycle costing	Based on LCC results for the buildings and public spaces	5.1
	ECO2.2 – Space efficiency	The built density index is 4.28	5.0
	SOC1.2 – Social and profit oriented infrastructure	The score for the access to social and profit oriented infrastructure is assumed to be 50 (reference value)	0.9
	SOC2.2 – Sojourn quality in public spaces	No greenery in the public space (square) - good solar access - no summer shading by trees	0.0
	SOC3.1 – Open space supply	Public open space of 0.28 m²/m² UFA - no private open space	1.4
	SOC3.2 – Accessibility	The score for the access to essential infrastructure is assumed to be 15 (reference value)	0.3
	TEC1.1 – Energy technique	The primary energy factor for space heating is 1	0.5
	TEC1.3 – Rain water management	Reuse of rainwater in buildings - rainwater infiltration - only emergency overflow connected to surface water	0.6
	TEC3.1 – Quality of traffic system	Station at less than 20 min - 1 bus line - frequency of 1 bus per hour - no bicycle path - footpaths	0.5
	TEC3.3 – Quality of public transport infrastructure	The public transport stop is located at 750 m - no intermodal platform at 350 m	0.0
	TEC3.4 – Quality of cycling infrastructure	No cycling infrastructure	0.0
		TOTAL	**19.4**

* GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, AP = Acidification Potential, EP = Eutrophication Potential

Figure D.27: DGNB scores for the reference new neighbourhood (Model 4_apartment).

Sustainability measures	Assessment issues	Description	Score (%)	Δ REF (%)
M1_timber	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	+0.0
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	5.1	
M2_recycled materials	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	-2.9
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ENV2.4 – Resource saving infrastructure	More than 10% of the mass of materials used in the public realm is reclaimed and more than 60% is recycled	0.4	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	1.8	
E1_non-insulated	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	0.9	-1.1
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	0.9	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.8	
E2_passive standard	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.5	+0.5
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.6	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	5.2	
E3_oil boiler	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	0.9	-1.0
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.1	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.8	
E4_heat pump	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.2	-0.6
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	5.1	
	TEC1.1 – Energy technique	The primary energy factor for space heating is 2.5	0.0	
E5_no PV	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.2	-0.2
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.2	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	5.2	

* GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, AP = Acidification Potential, EP = Eutrophication Potential

Figure D.28: DGNB scores for the sustainability measures related to material use and operational energy use (Model 4_apartment).

Sustainaibility measures	Assessment issues	Description	Score (%)	Δ REF (%)
W1_no rainwater tank	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	-0.4
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ENV2.6 – Water cycle system	Drinking water use of 2.9 l/m².day - no reuse of rainwater - local infiltration - separated sewer	0.5	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	5.1	
	TEC1.3 – Rain water management	No reuse of rainwater - rainwater infiltration - only emergency overflow connected to surface water	0.4	
W2_combined sewer	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	-0.9
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ENV2.6 – Water cycle system	Drinking water use of 2.7 l/m².day - reuse of rainwater in buildings - no infiltration - combined sewer	0.2	
	TEC1.3 – Rain water management	Reuse of rainwater in buildings - no infiltration - combined sewer	0.2	
W3_permeable areas	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	-0.1
	ENV1.2 – Water and soil protection	The percentage of sealed areas is 44%	0.6	
	ENV1.4 – Biodiversity and integration	The biotope area factor is 0.27	0.1	
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ENV2.6 – Water cycle system	Drinking water use of 2.7 l/m².day - reuse of rainwater in buildings - permeable materials and infiltration -	0.7	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.7	
	TEC1.3 – Rain water management	Permeable paved areas - reuse of rainwater in buildings - rainwater infiltration - no connection to surface water	0.8	
L1_urban land	-	No credit for a development on urban land	0.0	0.0
L2_arable land	-	No credit for a development on arable land	0.0	0.0
L3_park	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.3	+2.2
	ENV1.2 – Water and soil protection	The percentage of sealed areas is 44%	0.6	
	ENV1.3 – Change in urban climate	The urban climate index is 1.14	0.5	
	ENV1.4 – Biodiversity and integration	The biotope area factor is 0.65	0.3	
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.4	
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	6.4	
	SOC2.2 – Sojourn quality in public spaces	More than 80% of the public space area is green (park) - good solar access - summer shading by trees	0.1	

* GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, AP = Acidification Potential, EP = Eutrophication Potential

Figure D.29: DGNB scores for the sustainability measures related to operational water use and primary land use (Model 4_apartment).

Sustainability measures	Assessment issues	Description	Score (%)	Δ REF (%)
T1_urban area	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.8	+3.0
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.6	
	SOC1.2 – Social and profit oriented infrastructure	The score for the access to social and profit oriented infrastructure is 100	1.8	
	SOC3.2 – Accessibility	The score for the access to essential infrastructure is 30	0.5	
	TEC3.1 – Quality of traffic system	Station at less than 5 min - 2 bus lines - frequency of 4 buses per hour - no bicycle path - footpaths	0.7	
	TEC3.3 – Quality of public transport infrastructure	The public transport stop is located at 50 m - intermodal platform (train/bus) at 350 m	0.8	
T2_rural area	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.1	-0.9
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.2	
	SOC1.2 – Social and profit oriented infrastructure	The score for the access to social and profit oriented infrastructure is 38	0.7	
	SOC3.2 – Accessibility	The score for the access to essential infrastructure is 0	0.0	
	TEC3.1 – Quality of traffic system	Station at less than 25 min - 1 bus line - frequency of 1 bus per hour - no bicycle path - footpaths	0.5	
	TEC3.3 – Quality of public transport infrastructure	The public transport stop is located at 1300 m - no intermodal platform at 350 m	0.0	
T3_bicycle path	ENV1.1 – Life Cycle Assessment	Based on LCA results for GWP, ODP, POCP, AP and EP*	1.5	+0.9
	ENV1.2 – Water and soil protection	The percentage of sealed areas is 75%	0.5	
	ENV1.3 – Change in urban climate	The urban climate index is 0.52	0.0	
	ENV1.4 – Biodiversity and integration	The biotope area factor is 0.15	0.1	
	ENV2.2 – Total primary energy demand	Based on LCA results for primary energy demand - proportion of renewable energy of 10%	1.5	
	ENV2.3 – Energy efficient building structure	The building compactness is 0.25	1.2	
		The percentage of solar oriented living areas is 87.5% and the factor for the active use of solar energy is 35%		
	ECO1.1 – Life Cycle Costing	Based on LCC results for the buildings and public spaces	4.8	
	ECO2.2 – Space efficiency	The built density index is 4.01	4.8	
	TEC3.1 – Quality of traffic system	Station at less than 20 min - 1 bus line - frequency of 1 bus per hour - bicycle paths - footpaths	0.8	
	TEC3.4 – Quality of cycling infrastructure	Qualitative cycling infrastructure	0.8	

* GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POCP = Photochemical Ozone Creation Potential, AP = Acidification Potential, EP = Eutrophication Potential

Figure D.30: DGNB scores for the sustainability measures related to user transport (Model 4_apartment).

Appendix E – Comparison of life cycle impacts, qualities and scores

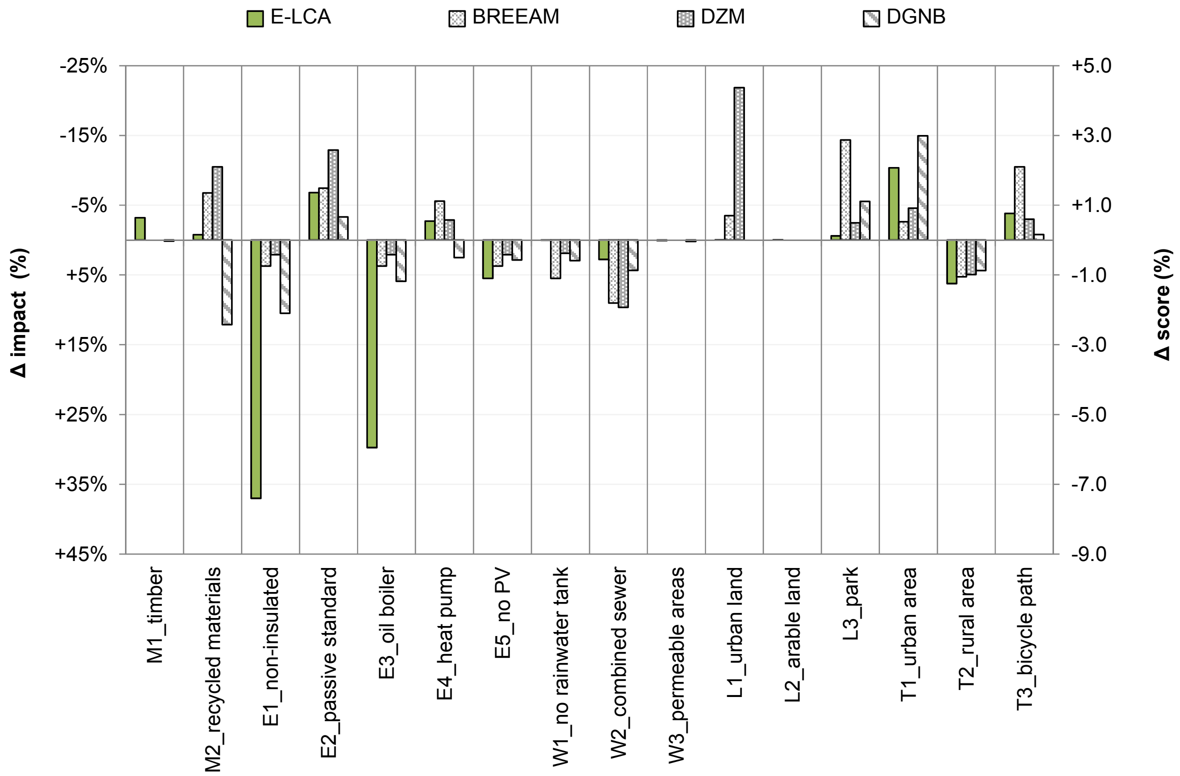

Figure E.1: Comparison of the E-LCA results for the sustainability measures with the BREEAM, DZM Wijken and DGNB scores (Model 2_semidetached).

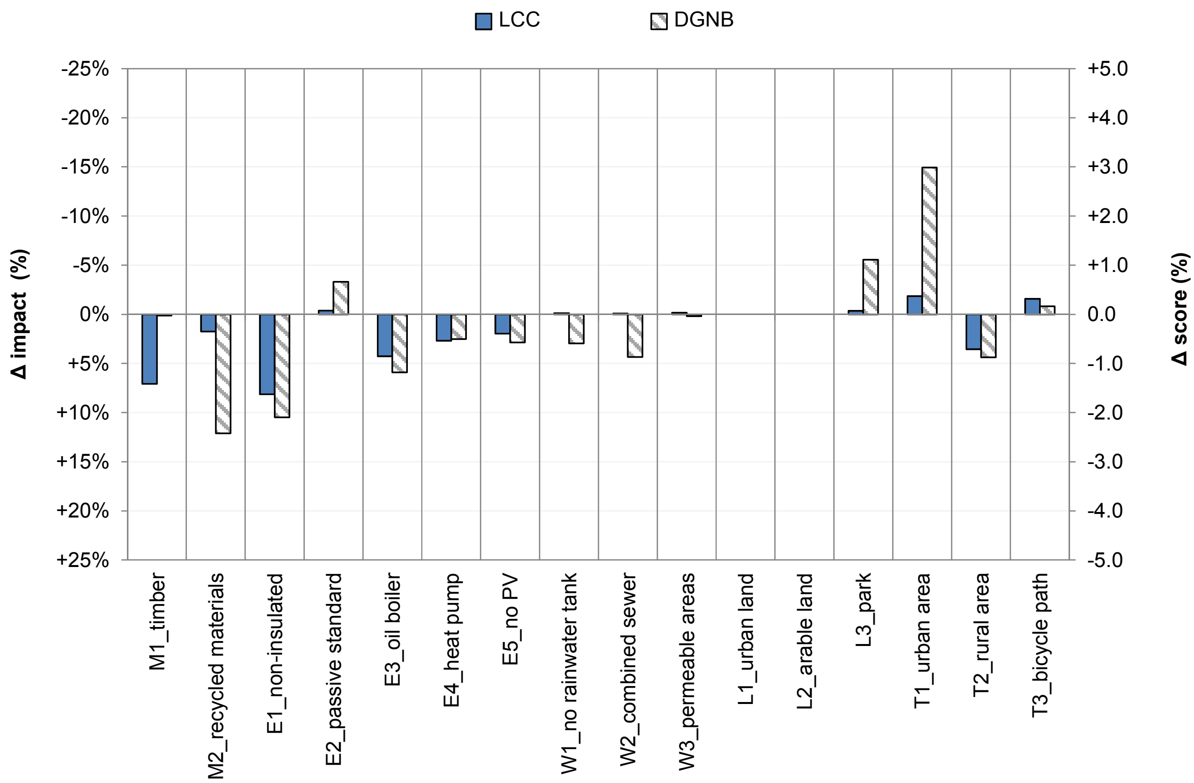

Figure E.2: Comparison of the LCC results for the sustainability measures with the DGNB scores (Model 2_semidetached).

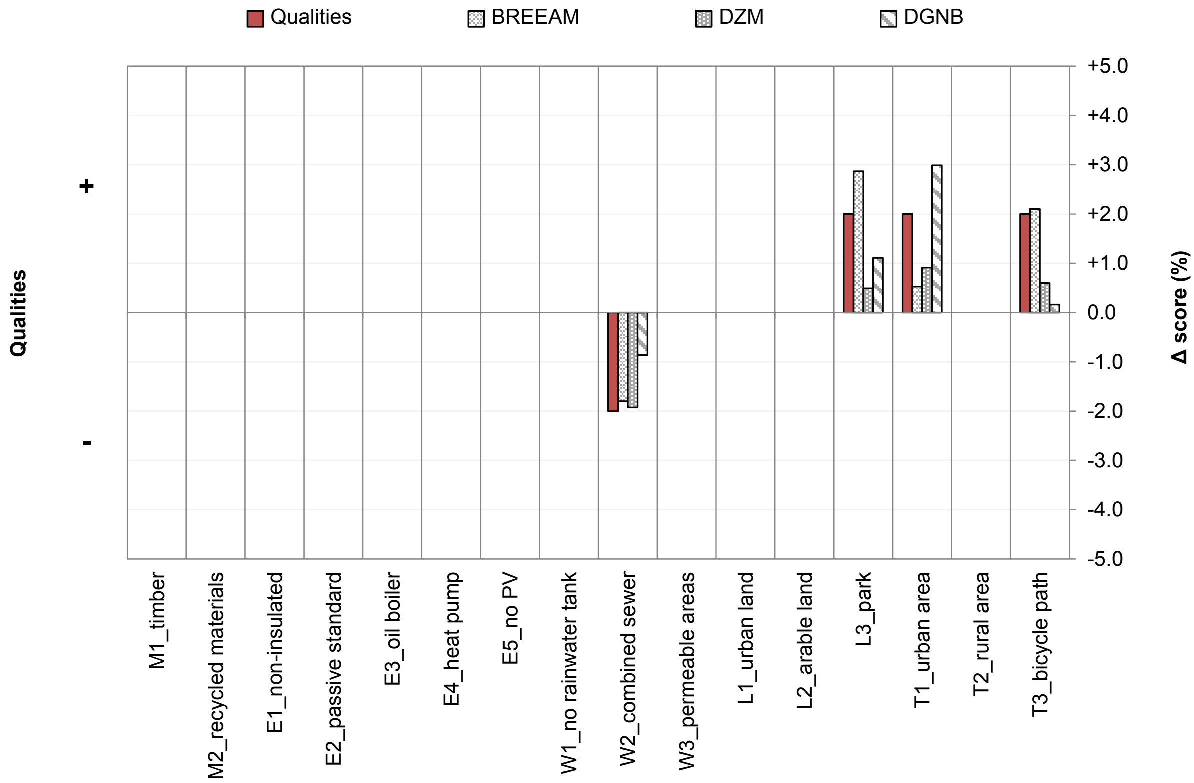

Figure E.3: Comparison of the qualities resulting from the sustainability measures with the BREEAM, DZM Wijken and DGNB scores (Model 2_semidetached).

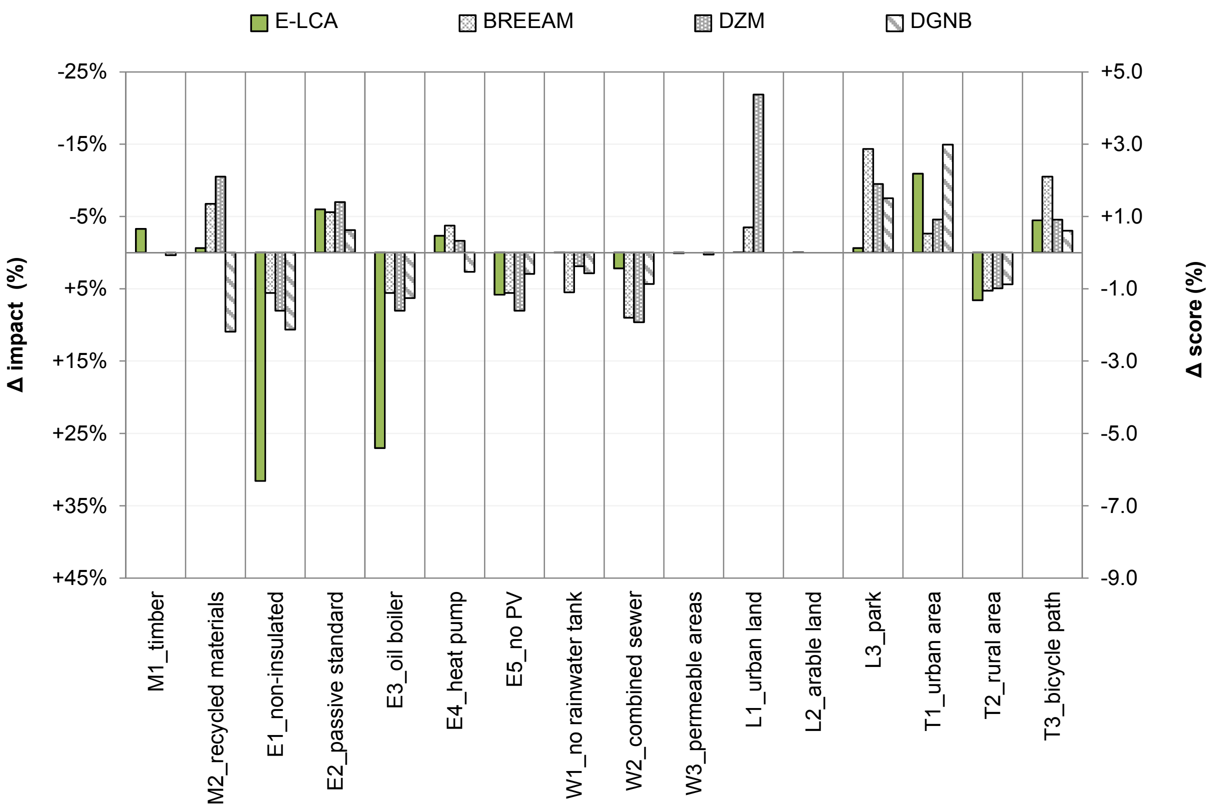

Figure E.4: Comparison of the E-LCA results for the sustainability measures with the BREEAM, DZM Wijken and DGNB scores (Model 3_terraced).

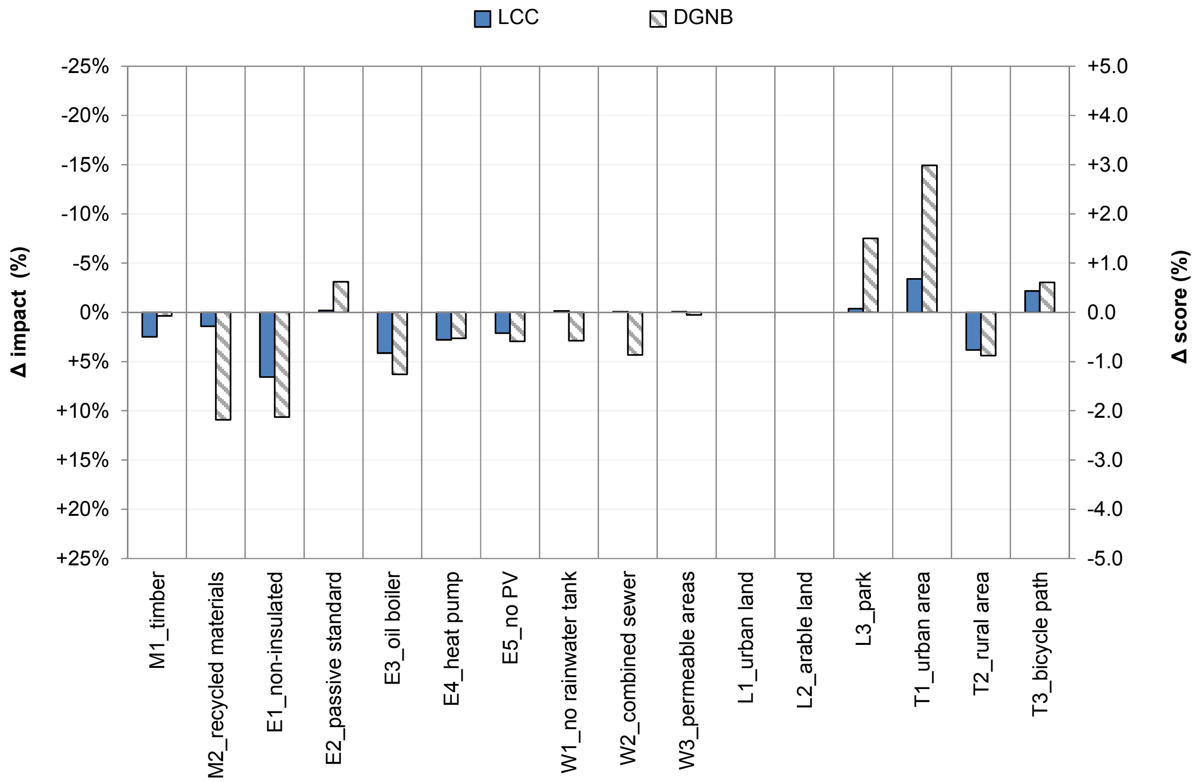

Figure E.5: Comparison of the LCC results for the sustainability measures with the DGNB scores (Model 3_terraced).

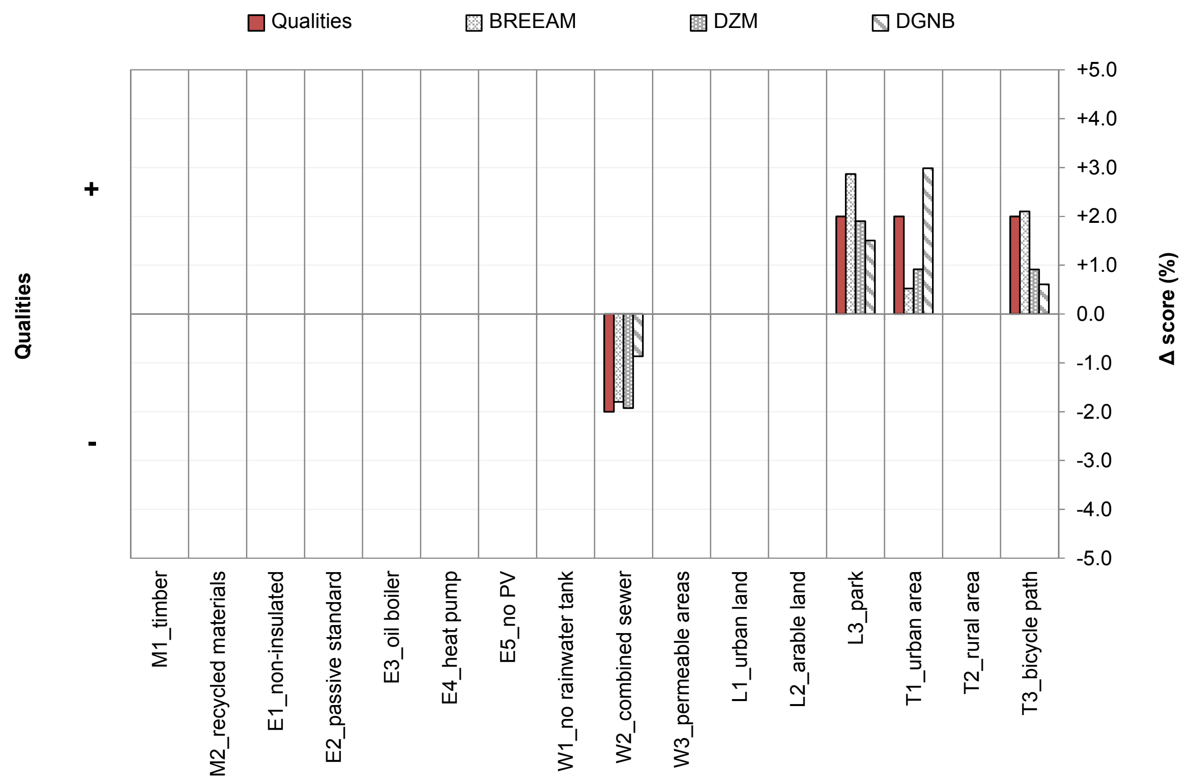

Figure E.6: Comparison of the qualities resulting from the sustainability measures with the BREEAM, DZM Wijken and DGNB scores (Model 3_terraced).

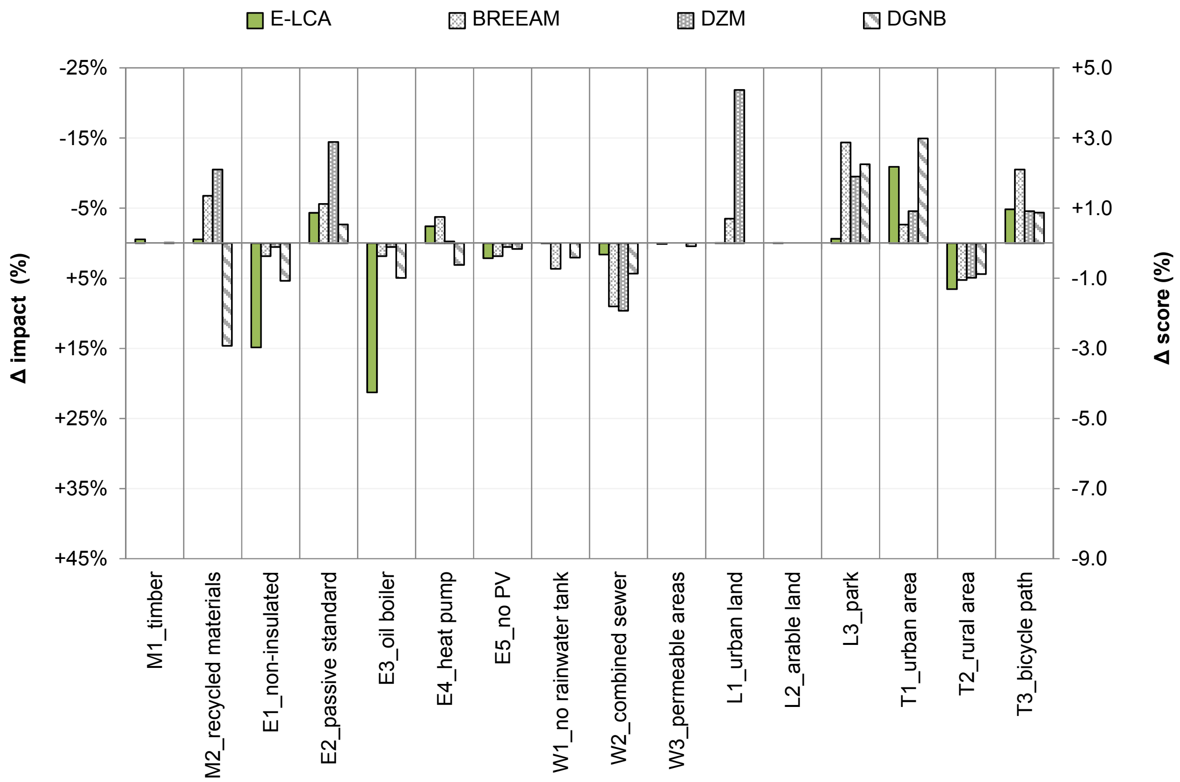

Figure E.7: Comparison of the E-LCA results for the sustainability measures with the BREEAM, DZM Wijken and DGNB scores (Model 4_apartment).

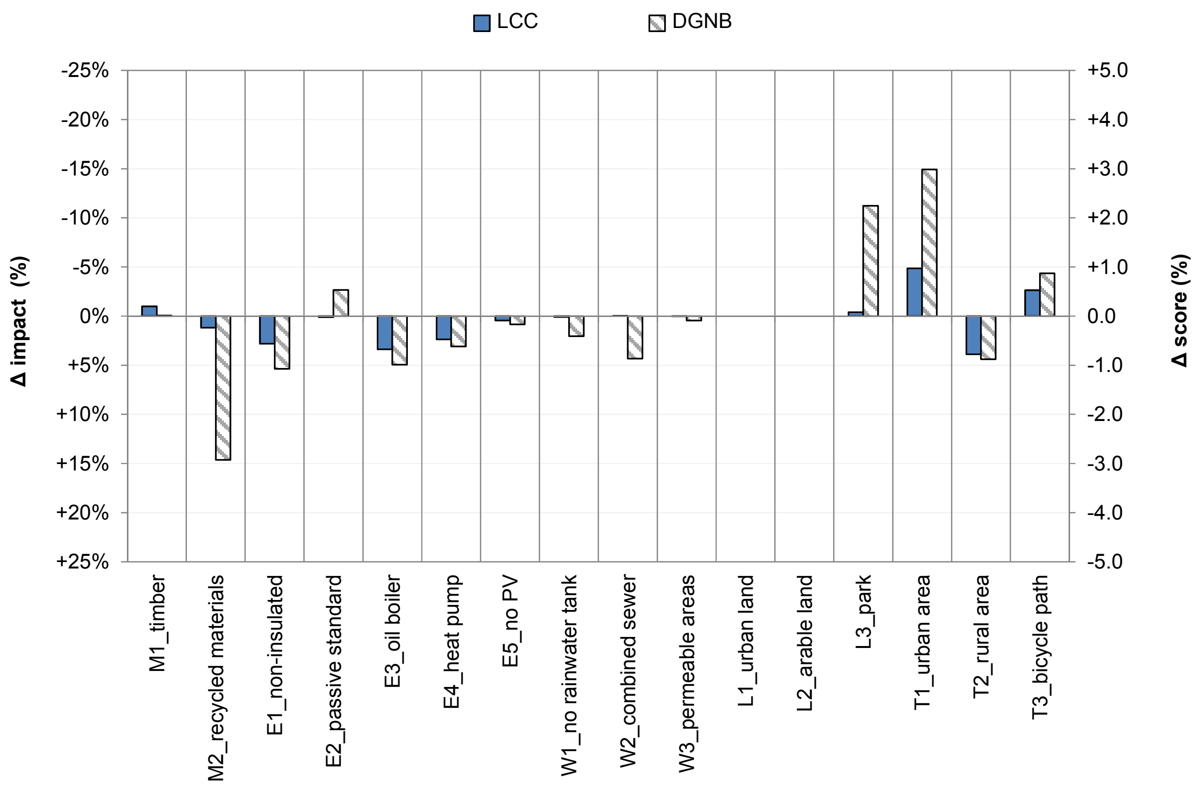

Figure E.8: Comparison of the LCC results for the sustainability measures with the DGNB scores (Model 4_apartment).

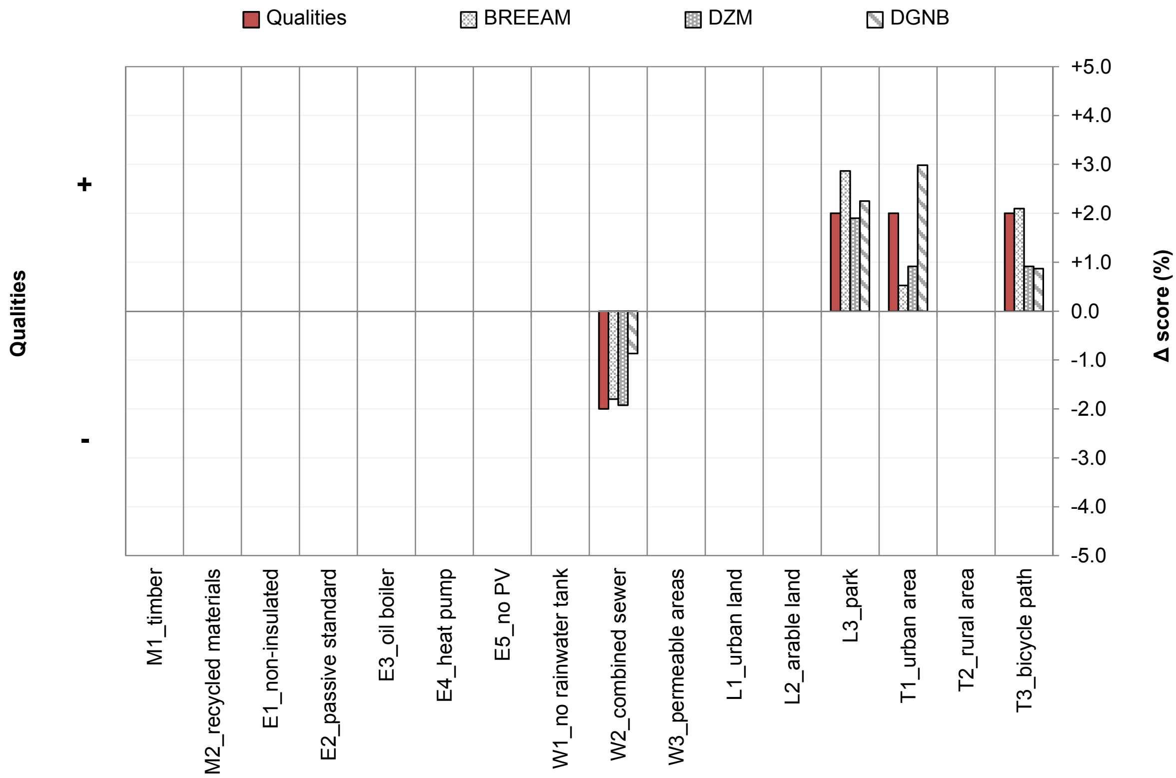

Figure E.9: Comparison of the qualities resulting from the sustainability measures with the BREEAM, DZM Wijken and DGNB scores (Model 4_apartment).

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Curriculum vitae

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Education

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